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Models for proliferation interdiction response analysis

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THESIS

MODELS FOR PROLIFERATION INTERDICTION RESPONSE ANALYSIS

By

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September, 1994

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MODELS FOR PROLIFERATION INTERDICTION RESPONSE ANALYSIS

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The proliferation of nuclear weapons poses a serious threat to the United States, its allies, and over-all world security. The United States seeks to dissuade or prevent new countries from acquiring nuclear weapons capabilities. This thesis constructs two models to aid decision makers in selecting strategies to interdict these proliferation efforts. The first, a "what-if" PERT/CPM model, provides an overall picture of the proliferation process. The graphical display is used to select activities to interdict, and to analyze the outcome of the choices. The second, an optimal interdiction model, selects the optimal activity(ies) for interdiction subject to risk constraints. Several runs with different numbers of interdiction points were made to test the optimal interdiction model. These results are further analyzed with the aid of the PERT/CPM model. The models, when used together, prove to be useful in selecting the optimal activities to interdict in the proliferation process.

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EXECUTIVE SUMMARY

The proliferation of nuclear weapons poses a serious threat to the United States, its allies, and over-all world security. The United States seeks to dissuade or prevent new countries from acquiring nuclear weapons capabilities. If political or economic measures prove ineffective in discouraging or blocking a proliferator, military action may become necessary.

To support a strategy of delaying or preventing the development of nuclear weapons, this thesis develops two decision aids or tools for estimating the delay caused by certain actions, possibly military. The decision aids can be used by decision makers in the selection of a specific course of action to hinder the weapons program.

The two approaches to aid the decision maker in the development of an interdiction strategy are a "what-if" PERT/CPM model and an optimal interdiction model. The basis of both approaches is the PERT/CPM (Program Evaluation and Review Technique/Critical Path Method) methodology. Both decision aids involve the selection of points for interdicting the nuclear weapons program of a proliferating country. The "what-if" PERT/CPM model implementation allows the user to manually select the activity for interdiction. The user can then graphically interpret the effects, including delay in project completion and the associated cost, social and economic impact, possible retaliatory response, and the required effort of the interdictor. This model is implemented in the commercially available software package MacProject Pro.

In the optimal interdiction model, the set of interdiction activities is selected to maximize the induced

delay in completing the project. An extension of this model allows the user to include constraints that limit the cost and impacts of the interdiction effort to be under specified levels. Both the model and its extension are implemented in GAMS. Illustrations using data based on two types of nuclear weapons programs demonstrate that the model provide useful information for decision making.

Several runs of the optimal interdiction model, with two different data sets, were made to test the effectiveness of from one through three activity interdiction strategies. The results obtained show that the optimal interdiction activities can be solved with an operations research approach. In a few of the multiple activity interdiction runs the activities selected for interdiction were not on the original critical path, and thus an interdiction induces both a delay and a new critical path. These results show the critical path may not be best source of activities to interdict.

To summarize, this thesis demonstrates that developing a strategy for the control of the proliferation of nuclear weapons can be aided by two decision tools: an optimal interdiction model and a "what-if" PERT/CPM model. These models have their respective strengths and weaknesses. Developing a good interdiction strategy depends on the subjective judgment of experts that may be difficult to capture in an optimization model, and we do not advocate the use of the optimal interdiction model as a stand-alone decision aid. Nevertheless, the analysis we have shown here indicates that the optimal interdiction model can provide non-trivial insights to interdiction strategies under the chosen constraints.

I. INTRODUCTION

Chapter I provides a background of the issues currently surrounding the proliferation of nuclear weapons. Section A presents a history from the beginning of the nuclear age through China's acquisition of a nuclear weapon in 1964. Second-generation proliferators, those who have nuclear weapons and those who want nuclear weapons, are discussed in Section B. The present nonproliferation regime is described in Section C. Current U.S. policy and a discussion of counterproliferation issues are covered in Section D. Readers knowledgeable in the proliferation area could proceed directly to Chapter II.

A. BACKGROUND

1. Beginnings of Proliferation

Since the 1930's certain countries throughout the world have sought to possess nuclear weapons. Two of the more advanced nations in the search for military uses of atomic power at that time were the Germans and the Italians. After Hitler and Mussolini came to power, fears of the future of nuclear power and difficult conditions for scientists in these nations lead many eminent nuclear physicists to emigrate to the United States. These events spurred President Roosevelt to begin the U.S. nuclear weapons program, the Manhattan Project, in 1941. [Ref. 1]

The events of World War II slowed and eventually halted the nuclear weapons aspirations of both Germany and Italy. During the war, the United States undertook top-secret efforts to acquire information, personnel and hardware relating to the German atomic program; the project was code-named "ALSOS." In April 1945, American forces captured a number of nuclear facilities and atomic scientists, including Werner Heisenberg, Kurt Diebner, and Otto Hahn, the discoverer of atomic fission. [Ref. 1, p.24] Though the United States acquired a great deal of useful information, the Soviet Union also gained much information and materials on their march from the east. The United States was able to use the information to achieve its nuclear ambition as early as 1945. The United States demonstrated its abilities twice during August of that year at Hiroshima and Nagasaki.

The Soviet Union was next to achieve status as a member of the nuclear weapons club. With all the knowledge, facilities and materials gained by the takeover of the German effort, the Soviets were able to detonate a nuclear device on August 29, 1949. This represented the beginning of the nuclear standoff between the world's two superpowers. [Ref. 2]

The next member of the prestigious club was Great Britain. It began a nuclear program before the United States in 1939. The United States asked to join in the British effort in late 1940, but was rebuffed, with the British agreeing only to technology exchange. By 1943, with the war depleting required resources, the roles were reversed and Great Britain asked for U.S. assistance. The United States allowed both Great Britain and Canada to participate with the Manhattan Project. Following the war the British hoped to continue to work with the United States, but the McMahon Act(1946) prohibited collaboration on nuclear weapons matters with any foreign power. The Soviet detonation of an atomic bomb in 1949 resulted in an amendment to the McMahon Act in 1950 to allow greater U.S. support of the British effort. By October 1952, with

Winston Churchill back in office, Great Britain detonated its first nuclear weapon. [Ref. 2]

France was the next and most recent western nation to join the club. Though a sophisticated French nuclear scientific program, lead by Joliot-Curie, was begun in the early 1930's, World War II put an end to their effort. The post Second World War push consisted mainly of basic research and commercial nuclear power development. In 1954 the French decided the production of a nuclear weapon was politically feasible and in December 1956 began a program. By 1958 France had developed its own nuclear weapons and delivery systems and began to build its own nuclear triad, of missiles, submarines and bombers. [Ref. 2]

The last declared nuclear power is the People's Republic of China. Its program began in 1954 despite Mao Zedong's disparaging remarks about the bomb. The program progressed well under the tutelage of Soviet scientists, engineers and technicians until 1959, when China became angered at not receiving open access to Soviet knowledge. By 1960, the Soviets pulled its scientists out of China and refused all technical assistance. These events led to a rift in Sino-Soviet relations. The detonation of a device in October 1964 led to China's nuclear independence. China's weapons are of little strategic concern to the United States due to limited numbers and range. An area of concern to the United States is the assistance China provides to proliferating states in terms of technology, materials and equipment. [Ref. 3]

B. CURRENT PROLIFERATION EFFORTS

In addition to the five declared nuclear weapons states there are three types of proliferators in the world today. The first are the "De facto Nuclear Weapon States". This status is given to those countries believed to possess nuclear weapons or the ability to construct weapons in a short period of time. The "De facto Nuclear Weapons States" will be covered in section 1. The second proliferation concern is with respect to the Soviet break-up. How each of the now independent states, many with control of former Soviet nuclear facilities, will react on the issue of proliferation is unknown. The issues concerning these "Undecided Nuclear Inheritors" are covered in section 2. The last and greatest concern are the "Aspiring Nuclear Weapon States". These are nations building weapons to gain supremacy over their own region and possibly foster global intentions. The "Aspiring Nuclear Weapon States" are discussed in section 3. A world map with the current proliferation concerns is shown in Figure 1.

1. De Facto Nuclear Weapon States

Several countries in the past two decades have joined the nuclear family, either overtly or covertly. India, was the first when it detonated a "peaceful" nuclear device in 1974. India is known to stockpile nuclear weapons material but has made no overt effort to actually maintain weapons. [Ref. 2]

India's neighbor to the west, Pakistan, is also believed to possess nuclear weapons capability. Many believe the Pakistanis have 5 or 6 weapons and fighter aircraft capable of delivery. The U.S. government has

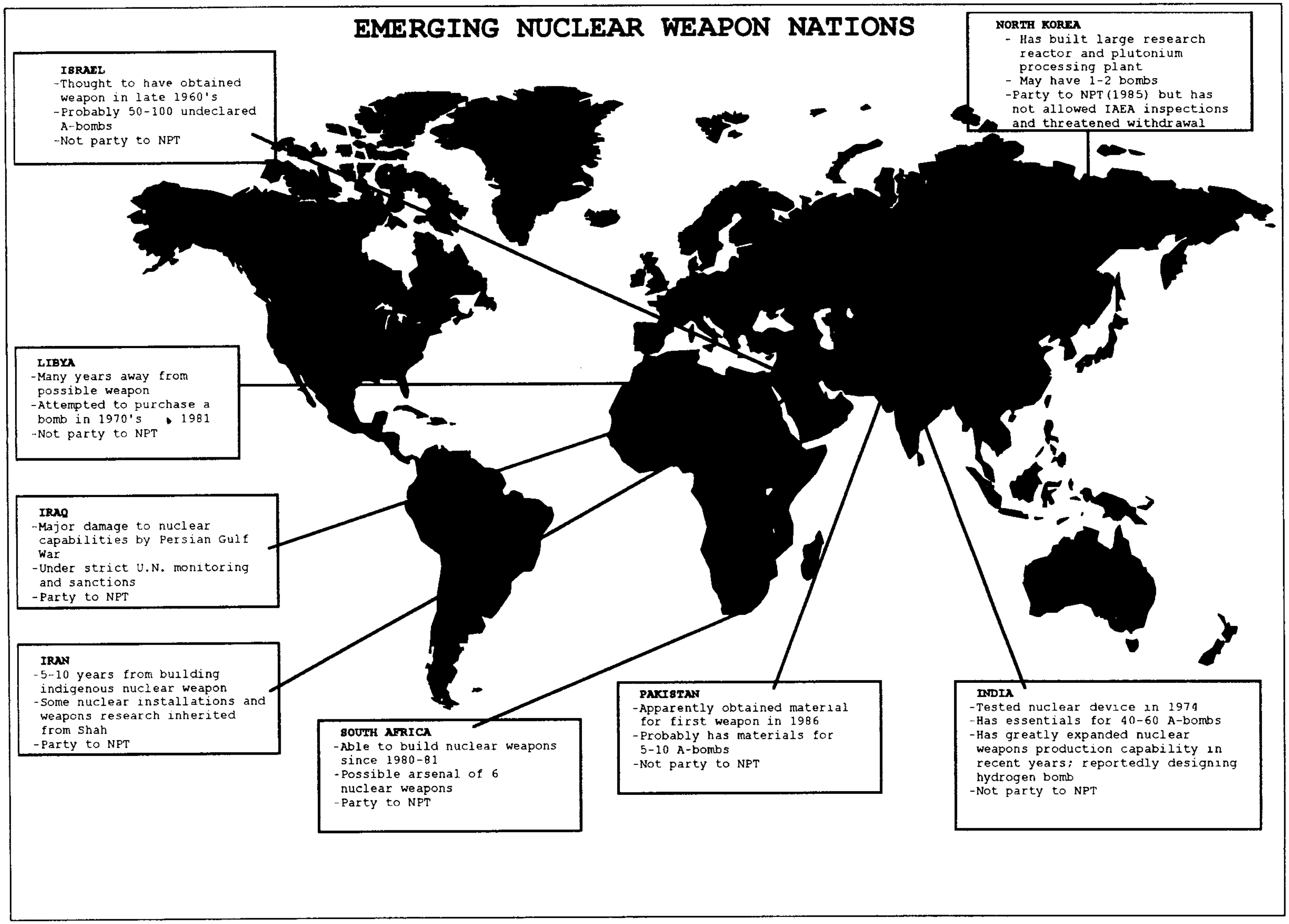


Figure 1. Current World Proliferators. After Ref. [1].

vacillated as to whether to believe or publicly confirm these suppositions. Pakistan is not an NPT member and does not permit IAEA inspections. [Ref. 4]

A third "De facto Nuclear Weapon State" with possible nuclear capability and the means to employ it at short notice is Israel. The Israelis are believed to have a clandestine arsenal of about 100 weapons. With a completely in-house effort of technology and materials, verifying the presence of nuclear weapons is difficult.

South Africa is the last of the "De facto Nuclear Weapon States". The South African government admitted to constructing six nuclear weapons. Subsequently, it has disassembled its nuclear arsenal. South Africa signed the Non-Proliferation Treaty in 1991 and has opened its facilities to nuclear inspections. The combination of a change in leadership and a strong technology base makes the future of South Africa's nuclear effort or "non-effort" unclear. [Ref. 4,p. 6]

Though the use of a weapon by a "De facto Nuclear Weapon State is remote, the fact these nations possess the capability is a concern. Regional instabilities could lead one of these nations to the brink of nuclear conflict. The situation in the Middle East does cause some concern. Israel could retaliate with a nuclear strike if they are attacked with chemical or biological weapons by a neighbor; however, current peace efforts in the region are making this possibility more remote.

2. Soviet Break-up

With the downfall of Communism and the breakup of the Soviet Union into individual states, a new risk in nuclear proliferation has developed. The first area of concern is the emergence of three nuclear inheritors: Belarus, Kazakhstan and the Ukraine. These nations possess nuclear weapons that were once the property of the Soviet Union. The instability of these new governments leads to great uncertainty with respect to their future proliferation policies.

Another and more immediate problem is the leakage of nuclear technology, equipment, materials and experts. Transfer of nuclear products can occur by way of overt, over-the-counter sales, clandestine assistance to a proliferating country, or unauthorized leakage.

The final and more lasting concern is the unknown stance on the proliferation policy of the non-nuclear Soviet states. Many possess a great deal of materials, equipment and technology that went into building the U.S.S.R.'s large nuclear arsenal. The leadership in these newly born democracies could elect to pursue nuclear weapons and lead to a future world with many more nuclear states.

3. Aspiring Nuclear Weapon States

While the current proliferators cause concern to the world community, the "Aspiring Nuclear Weapon States" could pose a bigger problem. A major effort is currently being pursued by the Republic of North Korea. Because of its past effort, Iraq must be included in this category. Other less advanced countries include Iran, Libya and Algeria. These three countries are of less concern. While Libya and Algeria have research reactors, none have operational power reactors. None possess enough fissile material or the technology to assemble a nuclear weapon. However, they all possess delivery systems capable of a ranges over 100km. [Ref. 4] Thus, the largest immediate concern for these cases is the covert purchase of an operational weapon from a nuclear state (e.g., former Soviet states).

At one time, Iraq was a thorn in the side of the non-proliferation effort. It initially followed a path to producing a plutonium-based nuclear weapon. This effort was halted by the Israeli bombing of Iraq's non-operational reactor at Osirak in June 1981. Iraq then turned in a different direction in order to build a bomb - the enriched uranium cycle. Iraq spent billions of dollars and commissioned thousands of people to the project, code named Petrochemical-3. This effort was aided by the West's support of Iraq during the Iran-Iraq War. Though Iraq remained a member of the NPT, the Western nations neglected to enforce the NPT and allowed them to import nuclear technologies. [Ref. 5]

The onset of The Persian Gulf War in 1991 resulted in a dramatic setback of Iraq's nuclear program. Many of the primary targets for the allies were known or suspected nuclear facilities. With the Iraqi defeat, United Nations Resolution 687 enforced heavy inspection criteria on the Iraqi nuclear program. Though a great deal of technology and equipment was destroyed, many facilities went untouched during the bombing campaign. With the completion of current mandated inspections, there is no sure sign that the Iraqi nuclear program has ceased to exist.

The final source of proliferation concern is the Republic of North Korea. While North Korea is currently a member of the NPT, its commitment to the treaty is, at best, suspect and they have vacillated on the issue of withdrawing from the NPT. After years of delaying nuclear inspections (1985-92), it finally allowed limited inspections. In March 1993 North Korea denied any further IAEA access and announced its intention to withdraw from the NPT (which is permitted under the terms of the treaty). Upon U.S. diplomatic intervention in June, North Korea postponed its withdrawal.

The world community has made numerous attempts, using various approaches, to prevent nuclear proliferation in North Korea. Political progress toward reconciliation of the hostilities between North and South, led to the signing of a "Joint Declaration for a Non-Nuclear Korean Peninsula" in 1991. North Korea's agreement to IAEA inspections was given and subsequently rescinded several times over the past two years. The most recent nonproliferation effort was the threat of economic sanctions from the United Nations. While the threat of such sanctions are the most severe effort to date, in order to prevent or deter proliferation, there is the distinct possibility that the use of sanctions could lead to the requirement for military actions on the Korean Peninsula. With the recent passing of Kim Il Sung, future proliferation on the Korean peninsula is uncertain. [Ref. 4]

C. TREATIES AND CONTROLS

The nuclear nonproliferation regime, to include the use of international treaties, institutions and bilateral nuclear-trade agreements, has proven to be a major deterrent to the spread of nuclear weapons. A principal portion of this regime is the International Atomic Energy Agency(IAEA). The IAEA is a Vienna-based organization directly affiliated with the United Nations. The agency was founded in 1957 and currently has 110 signed members. The IAEA's primary function is the implementation of a program of on-site inspections, audits, and inventory controls. This program is generally referred to as IAEA safeguards. [Ref. 1, p.336]

The purpose of these safeguards is to prevent the diversion of peacefully obtained nuclear materials to military purposes. The safeguards are based on the timely detection and notification of any abnormalities. When inspectors are not on-site, container seals and cameras are used to detect diversions. In the event of a safeguards violation the IAEA has the authority to notify the United Nations Security Council, but cannot impose sanctions. [Ref. 1]

The Nuclear Non-Proliferation Treaty (NPT) represents the next step in the creation of the nonproliferation regime. The treaty, which went into effect on March 5, 1970 for 25 years, divides the countries that signed it into two categories: Nuclear Weapon States (the United States, the Soviet Union, Great Britain, France and China) and Non-Nuclear States (other member countries). The NPT prohibits all members, except the five Nuclear Weapon States, from acquiring nuclear weapons. It requires all non-nuclear members to implement a safeguards agreement with the IAEA, covering all nuclear materials that could be used in weapons programs. A conference in 1995 is set to discuss an extension of the treaty. [Ref. 4]

Two smaller treaties have also been instrumental in the nonproliferation regime. The Treaty of Tlatelolco (1968), created a Latin American nuclear-weapons free zone. The parties agreed not to manufacture, test, acquire weapons or allow others to place them on their territory. The Treaty of Raratonga (1986) created a South Pacific nuclear-weapons free zone based on the same principles as Latin America. [Ref. 4]

A Nuclear Suppliers Group also plays an important part of the nonproliferation regime. The group is based on the Non-proliferation Treaty Exporters Committee (Zangger Committee) which established IAEA safeguards and a "trigger list" for nuclear materials and equipment that is exported. The major provisions of the agreement require that before nuclear material, equipment or technology can be transferred, the receiving country must:

1. Pledge not to use the transferred materials to produce nuclear weapons.
2. Accept international safeguards on all transferred materials.
3. Provide security for materials to prevent theft or sabotage.
4. Agree not to transfer materials to a third party.

These provisions are currently being adhered to by the following nations: the United States, Great Britain, France, Germany, Japan, Canada, all former Soviet States, Belgium, Italy, the Netherlands, Sweden, Switzerland, Czechoslovakia, Poland, Australia, and Finland. [Ref. 1, pp. 348-352]

D. UNITED STATES NONPROLIFERATION POLICY STATEMENT

1. Enhanced Nonproliferation Efforts

The most recent example of U.S. policy on non-proliferation is described by a release from the Office of the Press Secretary to the President dated September 27, 1993. The fact sheet discussed the policy of non-proliferation and export controls.

The President established a framework for U.S. efforts to prevent the proliferation of weapons of mass destruction and the missiles that deliver them. He outlined three major principles to guide the nonproliferation and export control policy:

1. Our national security requires us to accord higher priority to nonproliferation, to make it an integral element of our relations with other countries.

2. To strengthen U.S. economic growth, democratization abroad and international stability, we actively seek expanded trade and technology exchange with nations, including former adversaries, that abide by global nonproliferation norms.

3. We need to build a new consensus -- embracing the Executive and Legislative branches, industry and public, and friends abroad -- to promote effective nonproliferation efforts and integrate our nonproliferation and economic goals.

The president reaffirmed U.S. support for a strong, effective nonproliferation regime that enjoys broad multilateral support and employs all means at our disposal to advance our objectives.

Key elements of the policy follow:

1. Comprehensive approach to control the growing accumulation of fissile material from nuclear weapons and within civil nuclear programs.

2. Uniform use of export controls applied by all suppliers.

3. The United States will make every effort to secure the indefinite extension of the NPT in 1995 and ensure that the IAEA has the resources needed to implement its vital safeguard responsibilities, and will work to strengthen the IAEA's ability to detect clandestine nuclear activities.

4. Diplomatic priority on achieving regional non-proliferation initiatives.

5. Proliferation will have a higher profile in our intelligence collection and analysis and defense

planning, and ensure that our own force structure and military planning address the potential threat from weapons of mass destruction and missiles around the world.

2. Counterproliferation

The nonproliferation regime is designed to dissuade non-nuclear states from starting nuclear weapons programs. When nonproliferation efforts fail to prevent the spread of nuclear weapons, counterproliferation may be required. The difference between the two efforts is that nonproliferation tries to prevent nations from seeking nuclear weapons and counterproliferation attempts to stop those who have started from attaining nuclear weapons, or those who have weapons to give them up. While there is not a universal definition of counterproliferation, it is generally regarded as the response to the proliferation of weapons of mass destruction and their means of delivery, at any state of development by means ranging from diplomacy to military interdiction. Counterproliferation is a potentially important instrument but is limited by international norms. It could be used to strengthen the current nonproliferation policies and regimes, but is not considered a substitute. Direct military intervention is generally regarded as a last resort because of the costs, operational difficulties and possible consequences. Three areas generally accepted as part of counterproliferation are diplomatic/political pressure, economic sanctions, and military means. The basis for these approaches will be discussed in the following sections.

a. Diplomatic/Political Pressures

The use of diplomatic pressure in an attempt to prevent proliferation of nuclear weapons comes in a variety of methods. The first is the direct diplomatic intervention toward the proliferator. Efforts to convince a country not to seek a weapon can be positive or negative in nature. The negative points are sometimes a greater concern to the proliferator, and often harder to bring about by the diplomat. Some of the issues presented to the potential proliferator are as follows:

1. Acceptance in or becoming an outcast of the New World order.
2. Increased opportunity to participate in world activities.
3. Increased security through concessions or military aid, or destabilization in the region.
4. Economic incentives or sanctions and embargoes depending on the level of cooperation.
5. Possible military intervention.

The second form of diplomatic pressure an indirect one and it is applied to countries aiding the proliferator. In this case, pressure is directed toward stopping those countries from supplying proliferation materials activities. The pressure applied can range from diplomatic discussions, to export controls, to the embargo of outgoing material.

Lastly, stabilization within the region can also prevent proliferation through diplomatic means. Formal discussions with adversaries of the proliferator can help reduce tensions and, in turn, prevent the perceived need for nuclear weapons. Such efforts have proven successful in the case of Brazil and Argentina. The use of diplomatic discussions brought both these countries back from the edge of proliferation. [Ref. 4]

b. Economic Sanctions

When diplomatic efforts fail, economic sanctions usually represent the next level of counterproliferation measures. These sanctions can be applied to either the proliferator or their supplying companies or countries. If applied to the supplier, the purpose of the sanctions are as a deterrent, not a punishment. U.S. laws and regulations provide for both criminal penalties and government procurement embargoes against U.S. and foreign companies in violation of U.S. export regulations. In some cases, the laws provide for aid or trade sanctions against countries that supply a means of proliferation to other countries. Some of these penalties include:

1. Cut-off of economic and military aid.
2. Forfeiture of property and assets.
3. Denial of arms transfers from the United States.
4. Blocking of international financial transactions.
5. Denial of assistance from international organizations in which the U.S. participates.

U.S. Law currently stresses the use of economic sanctions, over other types, toward a potential proliferator. The NPT practices a form of economic sanction by offering cooperation in civil nuclear technology exchange only to member nations. [Ref. 4]

c. Military Intervention

Military intervention as a means to prevent or reverse the efforts of the proliferating country can prove problematic. In January 1992, the United Nations Security Council declared the proliferation of Weapons of Mass Destruction to be a threat to international peace and security. This could open the door to tacit U.N. approval in using military efforts to deter proliferation. Even in cases not backed by a U.N. consensus, a military action could be justified, if the efforts were within the scope of self-defense.

There are several possible levels of military intervention. The first and least dangerous is the use of naval and air forces in a blockade to prevent the transfer of materials. This method proved relatively effective during the Persian Gulf War against Iraq in 1990-91. The next and possibly most volatile level of action is the covert use of forces against the proliferating country. These forces could be used to destroy technologies, materials equipment and possibly expertise used in the nuclear effort. The final method is the overt use of military forces against the nuclear program materials, equipment, and facilities of the proliferator. From a political standpoint it is generally necessary to build a consensus to justify these measures and in most cases the effort should remain short of all out war. [Ref. 4]

The decision to pursue an effort of military interdiction requires a well-thought strategy. The current counterproliferation policy stresses intelligence to attain real time information on a prolierant's activities. The decision on when to interdict and the specific activity or activities to interdict to achieve the maximum effect are paramount. This decision could be aided through the use of an operations analysis approach. The remainder of this thesis discusses, formulates and implements two models for use in the decision making process.

II PROBLEM STATEMENT

A. DEFINITION

The proliferation of nuclear weapons poses a serious threat to the United States, our allies and over-all world security. The United States seeks to dissuade or prevent the proliferation efforts of countries seeking nuclear capability as discussed in Chapter I, Section D. If political or economic measures prove ineffective in deterring a proliferator, military action may become necessary.

To focus on a strategy of delaying or preventing the development of nuclear weapons, United States Strategic Command (STRATCOM) is interested in a decision aid or tool that can be used to estimate the delay caused by certain actions, possibly military. The decision aid could be used by decision makers in the selection of a course of action, out of the myriad of choices, to deter the proliferator. Any decision made could have a dramatic effect on the proliferator, its neighbors and the United States.

Because the interdiction of a country's proliferation effort is of great magnitude, such a decision should encompass as much information as possible. Relevant information may come from a variety of sources, and include both general knowledge and classified information. General knowledge is based on area studies on the population, economy, social, military, and political situations. Classified information would come from secure sources both internal and international. This thesis will not include secure information for classification reasons.

The development of nuclear weapons consists of a network of activities to be completed sequencially. A delay in the effort can be achieved by interrupting one or more of the activities in the network. The interruption of an activity can come as a result of political, economic or military interdiction. A prime example of an effective military interdiction is Iraeli destruction of the Iraqi reactor at Osirak in 1981.

The factors to be considered when determining the activity to be interrupted are:

1. Additional time until completion of the weapons.
2. Monetary cost incurred by the proliferator.
3. Social impact on the population.
4. Economic impact on the country or region.
5. Possible retaliatory actions.
6. Required effort by the interdicting nation.

Factors 2 through 6 will be represented by ordinal data, and will be rated as to severity or effort.

The problem is then to select those activities to interdict so as to maximize the time delay of the project, while satisfying certain pre-specified constraints regarding the above listed factors.

B. THESIS OUTLINE

The remainder of the thesis concentrates on the development and implementation of two models: a "what-if" PERT/CPM model and an optimal interdiction model. The discussion is organized as follows.

Chapter III, section A describes the data used in both models, its derivation and generation. Section B contains methodology surrounding the development and implementation of the "what-if" PERT/CPM model; the PERT/CPM model also acts as a subproblem of the optimal interdiction model.

Section B also covers the application of MacProject Pro to solving the PERT/CPM model. Section C covers the derivation of the optimal interdiction model. Section D provides an interpretation constraint structure and implementetion of the optimal interdiction model in the General Algebraic Modeling System (GAMS). Section E is a short discussion of some related work.

Chapter IV analyzes the results from various runs of the optimal interdiction model and how they relate to the underlying PERT/CPM model. Chapter V discusses the conclusions drawn in the thesis and outlines some possibilities for follow-on research.

III METHODOLOGY

Two approaches to aid the decision maker in the development of an interdiction strategy are considered in this thesis. The basis of both approaches is the PERT/CPM (Program Evaluation and Review Technique/Critical Path Method) methodology which is discussed in section B. Both decision aids involve the selection of activities for interdicting the nuclear weapons program of a proliferating country. The "what-if" PERT/CPM model implementation allows the user to manually select the activity for interdiction. The user can then graphically view the effects, including delay in project completion and the associated cost, social and economic impact, possible retaliatory response, and the required effort of the interdictor. The second decision aid involves the optimal selection, from a set of allowable activities, the activity or activities to be interdicted and is described in section C. A discussion of the supporting data, to include how it was derived and sorted, and what is used in the models, is covered in section A.

A. DISCUSSION OF DATA

The data used in the two models is primarily the same. In the PERT/CPM model the data is in a descriptive form, so the decision maker can interpret it easily. This descriptive data is translated into a nominal scale for optimization model. Data generation is covered in the following sections.

1. Past Proliferation Efforts

In order to keep the thesis unclassified, data from current proliferation efforts could not be used. Instead published reports and IAEA inspection records were used as a basis for the data collected. Some raw data was subjective in nature and required interpretation.

To obtain a realistic data set for illustration, the proliferation efforts of recently completed nuclear programs are included. The data is based on studies of the proliferator's facilities and equipment. The locations of the facilities, surrounding population, and political situation all help to determine the resulting data set.

The construction of a nuclear weapon is a complex series of steps that begins with the purchase or mining of ore, and ends with the stockpiling of completed bombs. A basic layout of the production process is displayed in Figure 2. Two alternate processes may be used. Each process shares the same initial steps but they then split and subsequently only contain stockpiling as a common activity. A uranium-based program splits from the plutonium-based program after the enrichment phase. The uranium process consists of 30 activities, while the plutonium process consists of 55, of these totals, 20 are common to both programs.

2. Process Selection

The PERT/CPM model, which forms the basis of our mathematical models, does not include the possibility of performing certain activities or achieving more general objectives by one of several means. For example, how reactor fuel is obtained, by purchasing or production, must be known prior to formulating the PERT/CPM model, and similarly, the option of building nuclear weapons by the uranium or plutonium process cannot be an embedded choice in the model. We will assume that the means of completing each

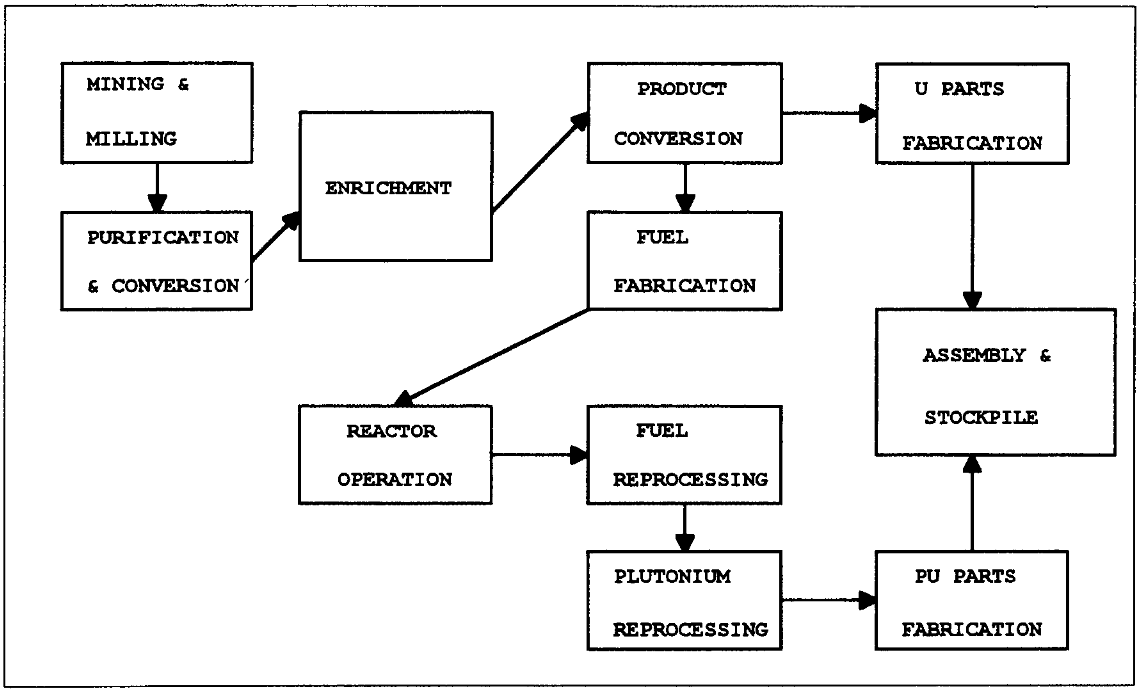


Figure 2. Nuclear Weapon Production Process.

activity and the overall program used by the proliferator is known. Nevertheless, it is convenient to maintain a database that includes information on the full range of possible activities. When running the "what-if" PERT/CPM model or the optimal interdiction model this allows the user to quickly ascertain the impact of the proliferator selecting alternate activities or processes.

3. Time to Completion

The completion time for a weapon depends on both the individual activity times and the chosen fissile material process, uranium or plutonium. The time to complete an activity, in turn, depends on how the activity is performed, e.g., purchasing or constructing. Most activities must be completed sequentially, but some can occur concurrently. The completion times for each activity are required for both the critical path calculation and the time delay for process interdiction.

4. Cost of Completion

The cost of overtly building a small-scale, plutonium-based nuclear weapon is approximately 300 million (1992$). A uranium-based weapon costs about 200 million (1992$). The cost of either program would be 10-20 times higher if efforts were made to keep the program secret. The largest cost in the plutonium cycle is the construction and operation of the nuclear reactor, approximately 100 million (1992$ overt). In the uranium cycle, the enrichment facility can account for about half of the capital cost of the weapon.

In the models we develop, each activity has an associated cost to completion. This cost relates to either the construction of the facility and equipment or the purchasing of same from another nation. All costs are in 1992 U.S. dollars. Table 1 shows a major process breakdown of the costs for building a plutonium-based weapon.

5. Social Impact

There are two important factors to consider when determining the social impact of an interdiction effort. First and most important is the location of the activity. In contrast to remotely located facilities, the collateral damage caused in a large population center would have a major impact. The reaction of the proliferating government and how it relates to the social issues in the country should also be considered. The social impact will be on a nominal scale between 1 and 10 for use in the optimization model. [Ref. 4]

Activities	1992 Costs (in mill$)
Capital Costs of Construction	
Uranium Mining Site (55,000t ore/yr):	1.5-15
Milling Plant (100t U_3O_8/yr):	8-9
Conversion Plant (85t uranium-metal/yr):	12-14
Fuel Fabrication Plant: (85t natural uranium fuel/yr)	6-10
30-MWt Production Reactor: (Brookhaven-type, air-cooled, graphite moderated, aluminum-clad natural uranium fuel; lower cost of "stripped down" facility with little shielding)	35-100
PUREX Reprocessing Plant: (85t heavy metal/yr, very low burn-up fuel, batch processing, recovering about 10kg of plutonium/yr; low estimate for facility with little radiation shielding)	12-36
RDT&E Costs for above Facilities: (10%-15% of the capital costs)	10-30
Start-up Costs for the above Facilities: (20%-25% of the capital costs)	15-45
Design and Manufacture of first Weapons: (capital cost of weapons lab, RDT&E of the design phase, and non-nuclear components, 20%-25% of total cost of plutonium production (all above costs)	20-65
Total Cost of First Plutonium-based Weapon	120-300

Table 1. Nominal Costs for an Overt Small-Scale Plutonium-Based Weapons Program. From Ref. [6].

6. Economic Impact

The severity of the interdiction effort has direct relation to the economic impact. It can be related on either a regional or national scale. The regional impact is proportional to the industrial destruction or agricultural contamination. The use of an embargo or large-scale destruction would have a significant national impact. The impact of both was demonstrated in the Persian Gulf War. Economic data is also related to a nominal scale. [Ref. 4]

7. Retaliatory Effort

The possible retaliation by a proliferator in response to an act of interdiction is a concern to the decision maker. Options available range from no retaliatory action to an all-out declaration of war on the interdictor. If the proliferator is covertly producing the weapon, the retaliation options may be more restricted in order to reduce the attention drawn from the world community. "Low end" scale retaliations are political in nature and consist of protesting to international organizations or severing political ties. "High end" retaliation consists generally of acts of violence. Local or international terrorism, limited war or a nuclear weapon response may be retaliatory options open to the proliferator.

8. Interdiction Effort

The interdiction efforts that the United States may consider depend on the complexity of the situation and the location of the facilities. Even the interdiction of the same activity will depend on how the facilities are constructed, e.g., above or below ground. The range of interdiction effort may be as low as diplomatic means and progress through economic methods up to military intervention. The largest effort expended would be full-scale war against the proliferator, as in Iraq. The use of Special Operations Forces to covertly destroy facilities is possible, but assets are limited and their loss would be costly to national security. Export restrictions on nuclear materials could serve the same purpose as military action with less risk. The interdiction effort will be rated on a nominal scale to be consistent with the optimization model.

The nominal relationship between the data collected and the data to be used in the optimization model is displayed in Table 2.

Nominal Value	Cost $million	Social Impact	Economic Impact	Retaliatory Response	Effort
1	>100	none	none	none	none
2	50-100	local damage	local damage	public complaints	public pressure
3	25-49	minimal death	major local damage	world-wide protest	U.N. pressure
4	15-24	major local damage	minor industry damage	formal U.N. protest	U.N./ economic sanctions
5	9-14	minor regional impact	major industry damage	formal U.N. sanctions	naval/ air blockade
6	6-8	major regional impact	economic sanctions	terrorist attack on ally	cruise missile attacks
7	4-5	minor national impact	minor regional damage	terrorist attack on U.S. soil	special operation forces
8	2-3	major national impact	major regional damage	wide spread terrorism	small-scale air strikes
9	1	social upheaval	economic turmoil	nuclear terrorism	large-scale air strikes
10	<1	large scale deaths	massive nuclear leakage	declaration of war on U.S or ally	declare war

Table 2. Relationship of Nominal Values to Interdiction Factors.

B. "WHAT-IF" PERT/CPM MODEL

The careful planning, scheduling, and coordinating of numerous interrelated activities is crucial in the successful management of any large-scale project. The completion of these tasks may be aided by formal procedures based on network optimization. The most prominent of these techniques is the PERT/CPM methodology. In the terminology of PERT/CPM the arcs are called "activities" and the nodes refer to "events". [Ref. 7] The precedence relations refer to the time-sequence in which certain activities must be performed. For example, in developing a nuclear weapon, fuel fabrication must be completed before reactor operation can begin, but the construction of facilities for both can be performed simultaneously.

Every PERT model can be represented by a directed acyclic network (see Appendix B), in which the nodes are defined as points in time when all activities on paths leading to that node have been completed. Arc lengths represent the time required to complete the corresponding activity. The precedence relationship between activities determine the network structure; in particular, one arc precedes another if and only if, the corresponding activity must be completed prior to its successor. The longest path from the "start" node to the "termination" node represents the minimum time it takes to complete the project. This longest path is called the *critical* path because a delay in completing any activity on that path will delay project completion.

The PERT problem can be formulated as the following network flow problem:

$$\text{maximize} \qquad \Sigma_{(i,j)\in A} TIME_{ij} x_{ij}$$

subject to $$\sum_{j:(s,j)\in A} x_{sj} = 1 \qquad (1)$$

$$\sum_{j:(i,j)\in A} x_{ij} - \sum_{j:(j,i)\in A} x_{ji} = 0 \qquad \forall i \in N,\ i \notin \{s,\ t\} \qquad (2)$$

$$\sum_{i:(i,t)\in A} x_{it} = 1 \qquad (3)$$

$$0 \le x_{ij} \le 1 \qquad \forall (i,\ j) \in A \qquad (4)$$

Where A and N are the sets of arcs and nodes, respectively. The index s represents the "start" and t, the "termination". In the objective function, $TIME_{ij}$ is the time to complete activity (i,j). The variable x_{ij} indicates whether activity (i,j) is on the critical path. When $x_{ij} = 1$, $TIME_{ij}$ is included in the summation which represents the length of the critical path. The constraints enforce the balance of flow at each node and, when viewed as a matrix, it is totally unimodular. This implies that the PERT problem has an optimal solution which is integer, i.e., x_{ij} is either 0 or 1.

There are many commercially available software packages to solve the above PERT problem. MacProject Pro [Ref. 8] from Claris Corporation is chosen for this thesis. MacProject Pro allows data such as $TIME_{ij}$, the precedence relationships which defines the arc set A, and other activity information to be entered easily. Given all the necessary inputs, MacProject Pro then solves the PERT problem and has facilities that allow users to view the solution graphically or in outline form.

By modifying the data in MacProject Pro and resolving the PERT problem, the users can conduct "what-if" analysis. For example, creating a delay on an arc (i.e., an activity) and resolving the PERT model, MacProject Pro provides a new solution that indicates the result of interdicting the activity. MacProject Pro provides the new (and hopefully longer) completion time as well as a new critical path. Table 3 provides results from several interdictions based on data in Appendix A. In all cases, MacProject Pro solved the PERT problem in under 5 seconds, and, in most cases the run time was negligible.

Interdicted Activities	Completion time (months)	Additional time due to interdiction
No Interdiction (Pu cycle)	115.5	0
Interdiction of spent fuel storage activity (Pu cycle)	121.5	6
Interdiction of reactor construction activity and spent fuel storage (Pu cycle)	193.5	78
No Interdiction (U cycle)	46.5	0
Interdiction of gaseous enrichment activity (U cycle)	70.5	24
Interdiction of gaseous enrichment facility construction and operation activity (U cycle)	86.5	40

Table 3. Results from "what-if" analysis.

C. OPTIMAL INTERDICTION PROBLEM

In this section, we generalize the PERT problem to a problem that selects a set of activities to interdict with the objective of inducing the maximum project delay. To formulate the optimal interdiction problem, define y_{ij} as a binary variable that equals 1 if activity (i,j) is to be interdicted and zero otherwise. Also, let $DTIME_{ij}$ denote the delay in completing activity (i,j) if it is interdicted, and let INTPTS denote the maximum number of activities that may be interdicted. Then optimal interdiction problem can be mathematically stated as:

maximize $f(y)$

$$\text{subject to} \quad \Sigma_{(i,j)\in A} y_{ij} \le INTPTS \tag{5}$$

$$y_{ij} \in \{0, 1\} \qquad \forall (i, j) \in A$$

where

$$f(y) = \text{maximize} \quad \Sigma_{(i,j)\in A}(TIME_{ij} + DTIME_{ij} y_{ij}) x_{ij}$$

subject to Equations (1) - (4)

This optimal interdiction model has the following interpretation. First, the interdicting country selects at most INTPTS activities to interrupt. The inner maximization problem represents the situation faced by the proliferating country. In particular, the interdicted activities result in delays $DTIME_{ij}$ activated by the outer optimization's binary variables y_{ij} and induces a PERT problem of the form covered in section B. As a result of the interdiction, the proliferating country is expected to respond in an optimal manner, i.e., by computing the earliest project completion time via the PERT problem. This sequenced pair of optimization problems may be rewritten as the following single optimization problem:

$$\text{maximize} \quad \Sigma_{(i,j)\in A}(TIME_{ij} + DTIME_{ij} y_{ij}) x_{ij}$$

subject to Equations (1) - (5)

$$x_{ij}, y_{ij} \in \{0, 1\} \qquad \forall (i, j) \in A$$

Note the objective function of this problem is non-linear due to the $x_{ij}y_{ij}$ cross term in the objective function. However, the fact that both x_{ij} and y_{ij} are binary, allows the objective function to be made linear by introducing an auxiliary variable q_{ij} and additional constraints. This procedure produces the following linear integer program.

$$\text{maximize} \qquad \Sigma_{(i,\,j)\in A}\, TIME_{ij}x_{ij} + DTIME_{ij}q_{ij}$$

subject to Equations (1) - (4) and

$$q_{ij} \le x_{ij} \tag{6}$$

$$q_{ij} \le y_{ij} \tag{7}$$

$$x_{ij},\, y_{ij} \in \{0,1\} \qquad \forall (i,j) \in A \tag{8}$$

$$0 \le q_{ij} \le 1 \qquad \forall (i,j) \in A \tag{9}$$

From (6) and (7) and the maximization, q_{ij} equals 1 when both x_{ij} and y_{ij} equal 1. This corresponds to the case that activity (i,j) is on the critical path and being interdicted, thereby resulting in the addition of $DTIME_{ij}$ to constitute the delay in project completion. On the other hand, when either x_{ij} or y_{ij} but not both equal 1, q_{ij} is forced to zero since either case produces no delay.

D. MODEL EXTENSIONS

As presented in the previous section, the optimal interdiction problem does not restrict which arcs can be interdicted. However, in practice, this may be unreasonable since available resources are generally limited, and the impact on, and potential response of, the proliferator must be taken into account. This section presents a possible set of constraints that limit the number and types of activities to be interdicted. To present these constraints, define the following data:

$COST_{ij}$	Cost to complete the activity
SOC_{ij}	Social impact
$ECON_{ij}$	Economic impact
$RETAL_{ij}$	Retaliatory response
EFF_{ij}	Interdiction effort
$MXCOST_{ij}$	Maximum allowable activity cost
$MXSOC_{ij}$	Maximum allowable social impact
$MXECON_{ij}$	Maximum allowable economic impact
$MXRETAL_{ij}$	Maximum allowable retaliatory response
$MXEFF_{ij}$	Maximum allowable interdiction effort
INTPTS	Maximum number of activities to interdict
ADJ	Adjustment factor for cumulative effect

Then the extended optimal interdiction problem can be written as:

maximize $\sum_{ij}(TIME_{ij}x_{ij} + DTIME_{ij}q_{ij})$

subject to: Equations (1) - (9) and

$$\sum_{ij\in A} COST_{ij} \times y_{ij} \le INTPTS \times MXCOST \qquad (10)$$

$$\sum_{ij\in A} SOC_{ij} \times y_{ij} \le ADJ \times INTPTS \times MXSOC \qquad (11)$$

$$\sum_{ij\in A} ECON_{ij} \times y_{ij} \le ADJ \times INTPTS \times MXECON \qquad (12)$$

$$\sum_{ij\in A} RETAL_{ij} \times y_{ij} \le ADJ \times INTPTS \times MXRETAL \qquad (13)$$

$$\sum_{ij\in A} EFF_{ij} \times y_{ij} \le INTPTS \times MXEFF \qquad (14)$$

Constraints (9)-(13) limit the cost and various impacts due to the interdiction efforts specified by y_{ij} to be less than the maximum levels. Furthermore, the values of MXSOC, MXECON, and MXRETAL have an adjustment factor to restrict the cumulative effects of interdicting several activities. Whereas, MXCOST and MXEFF allow direct multiples of INTPTS to be accumulated.

It is this optimal interdiction problem and the above extension that were implemented and solved using GAMS [Ref. 9] with an integer program solver called XA [Ref. 10]. The GAMS program is listed in Appendix C and the next chapter discusses results from solving the above problem using two data sets.

E. RELATED WORK

Some of the related work to this formulation include:

(1) The CPM method of time-cost trade-offs in which a premium cost is paid (e.g., overtime labor) in order to accelerate completion of certain activities. In our case the analog is to delay the completion of the project for the longest possible time. [Ref. 6, ch. 10]

(2) A deterministic network interdiction model was formulated by R. Kevin Wood and R. Steinrauf to interdict drug operations in South America. While the drug traffickers were trying to maximize the flow on the network the interdictor was trying to minimize that flow by interdicting network arcs using limited resources. [Ref. 7 and Ref. 8]

IV RESULTS AND ANALYSIS

This chapter presents and analyzes solutions obtained from solving the optimal interdiction problem and its extension using two different sets of input data. One data set is from a uranium-based, gaseous enrichment nuclear weapons program and the other is from a plutonium-based, metal enrichment nuclear weapons program. Data from the latter process is included in Appendix D.

A. URANIUM-BASED, GASEOUS ENRICHMENT NUCLEAR WEAPONS PROGRAM

The uranium-based process consists of highly enriching uranium to a concentration above 90% U-235. To achieve this level of concentration, the uranium is cycled through multiple stages in the enrichment facility. Activities with the longer delay times are associated with interdicting the construction of the facilities housing production activities. Table 4 summarizes the interdiction results from the optimization model.

The CPU times in Table 4 are from a 66MHz, 486DX2 personal computer. The completion times also indicate that the additional delay is diminishing as the number of activities for interdiction increases. Considering the cost and impact of additional activity interdiction, Table 4 suggests that it may not be advantageous to consider more than one interdiction.

The result of the two activity interdiction may seem counter-intuitive when compared to the solution generated by the PERT problem. Interdicting the construction of the enrichment facility would add 15 months vice the 11 added by

	Number of activities to interdict			
Activity	0	1	2	3
Gaseous Enrichment		X	X	X
Enrichment Facility Construction				X
Purification Facility Construction			X	
UF_6 Reduction				X
Time to Completion	46.5 months	70.5 months	81.5 months	87.5 months
CPU time	1 sec.	1 sec.	29 sec.	10 sec.

Table 4. Summary of Uranium-Based Model Results.

the second interdicted activity. In reviewing the data set, the reason for this choice is the retaliatory response constraint. The cumulative effects of retaliation in selecting both the enrichment facility construction and enrichment process would exceed the acceptable retaliatory response risk. It is interesting to note that the construction of the purification facility was not on the original critical path. However, as a result of interdiction the proliferating country's critical path has been changed to include this activity.

The first two activities in the three activity interdiction model are infeasible for the two activity model. This combination is permissible in the three activity model because the cumulative risk constraints (in this case retaliatory response) depend on the number of allowed interdiction points. In other words, the interdicting country's willingness to accept cumulative risk is reflected in the number of permissible interdiction points. The induced critical path is different from either the one or two activity interdiction models.

B. PLUTONIUM-BASED, METAL ENRICHMENT NUCLEAR WEAPONS PROGRAM

The production of a plutonium-based nuclear weapon requires several more time-consuming and difficult processes than the uranium-based program. One such process is the requirement for the irradiation of uranium to produce plutonium. This process requires the construction and operation of a nuclear reactor, a major investment in both time and resources.

During preliminary testing, interdicting the construction of the reactor for the radiation process dominates, and prevents the optimization and PERT models from considering interdiction of other activities. In practice, the destruction of the reactor, during construction, is the best option to delay proliferation. However, unless the proliferation intention is widely known, a pre-emptive strike on the reactor would be premature. When the reactor is fully operational and the intention of building a weapons program is evident, it would be unacceptable to destroy the reactor.

To allow for the interdiction of other activities, the activity associated with reactor construction was made infeasible for interdiction but still acceptable in the critical path. Table 5 summarizes the results for the plutonium-based program without interdicting the irradiation process. Unlike the uranium-based program, the additional delay does not seem to diminish as the number of activities interdicted increases. This, however, is not unexpected since integer programs do not necessarily generate concave optimal value functions.

	Number of activities to interdict			
Activity	0	1	2	3
Spent Fuel Storage		X	X	
Shearing/ Leaching			X	
Milling Construction				X
Metal Enrichment				X
Fuel Reprocessing construction				X
Time to Completion	115.5 months	121.5 months	122.5 months	136 months
CPU time	3 sec.	18 sec.	297 sec.	41 sec.

Table 4. Summary of Plutonium-Based Model Results.

V CONCLUSION

This thesis has demonstrated that developing a strategy for the control of the proliferation of nuclear weapons can be aided through the use of two decision tools: an optimal interdiction model and a "what-if" PERT/CPM model. These models have their respective strengths and weaknesses. Developing a good interdiction strategy depends on the subjective judgment of experts that may be difficult to capture in an optimization model, and we do not advocate the use of the optimal interdiction model as a stand-alone decision aid. Nevertheless, the analysis we have shown here indicates that the optimal interdiction model can provide non-trivial insights to interdiction strategies given the chosen constraints.

The PERT/CPM model provides a more graphical and user-friendly over-all view of the process but can be cumbersome to operate in the "what-if" mode on its own. The combination of the two models provides a starting point to aid decision makers. The optimal interdiction model directs the decision maker to those activities which are the best to interdict with respect to the constraints chosen. From there, the decision maker can look to the PERT/CPM model for more in-depth guidance on the effects of their decision.

The uranium-based two activity interdiction model provides a good example of how the two models complement each other. The optimal activities for interdiction are the construction and operation of the enrichment facility. The decision maker can interpret this result and determine the best course of action. If based on intelligence information, the decision maker determined the enrichment activity operation phase was nearing completion, the interdicting country could destroy the facility. This would essentially return the proliferator to step one, and only require the interdictor to make one effort. It would not be as easy to arrive at this strategy with the use of the optimal interdiction model alone.

There are many areas of this thesis that require follow-on work. The first is in the area of data collection. The development of a real-time data set could prove a difficult task. The conversion of relevant world intelligence reports into a nominal data set would require the interpretation by experts in the field and development of a consensus on those results. Many of these interpretations would also depend on the decision makers themselves. Their feelings on the risks involved with counterproliferation could impact the nominal values. This data set would also require real-time update capability to match constantly changing world situations.

Capturing the time dynamics of the interdiction problem within the optimization model represents a challenging problem for future research. The models we have developed are based on what is essentially historical data and do not necessarily capture the notion of the "current status" of a proliferator's weapons program. The status of which activities have been completed, which are ongoing, and which are yet to begin may play an important role in developing an interdiction strategy. Based on the quality of intelligence reports there may be some level of uncertainty associated with a projects current status, and this factor hardly simplifies matters.

An additional area of uncertainty that may warrant future attention is the fact that an interdiction effort may not succeed with a probability of one. Moreover there may be random delays in the completion time of the activity associated with the degree of an interdiction success.

These areas of follow-on work represent important and challenging problems. The PERT/CPM model and the optimal interdiction models that we have developed lend themselves to such generalizations and could serve as launching points for such future studies.

APPENDIX A. PERT/CPM OUTLINE

Name	Duration (Months)	Cost (Million 92	Social Impact
Mining	2	5.00	local damage/2
Crushing/ Grinding	1	3.00	minimal death/3
Leach	1	3.00	minimal death/3
Ore Concentration	1	3.00	minimal death/3
Precipitation	1	1.00	minimal death/3
Filtration/ Washing	1	2.00	minimal death/3
Dissolution	.50	3.00	minor regional impact/5
Chloride Elution	.50	3.00	minor regional impact/5
Solvent Extraction	.50	3.00	minor regional impact/5
Fluoride Elution	.50	3.00	minor regional impact/5
Denitration	.50	4.00	minor regional impact/5
Oxide Reduction	.50	3.00	minor regional impact/5
Hydrofluorination	.50	2.00	minor regional impact/5
Fluorination	.50	2.00	minor regional impact/5
Mg Reduction	.50	3.00	minor regional impact/5
Carbothermic Reduction	1	5.00	minor regional impact/5
Metal Enrichment	20	65.00	minor regional impact/5
Aqueous Enrichment	14	40.00	minor regional impact/5
Gaseous Enrichment	24	45.00	minor regional impact/5
UF6 Reduction	1	5.00	minor regional impact/5

Name	Economic Impact	Retaliatory Response	Interdiction Effort
Mining	local damage/2	formal U.N. protest/4	Large-scale air strike/9
Crushing/ Grinding	local damage/2	formal U.N. protest/4	cruise missile attack/6
Leach	local damage/2	formal U.N. protest/4	cruise missile attack/6
Ore Concentration	local damage/2	formal U.N. protest/4	cruise missile attack/6
Precipitation	local damage/2	formal U.N. protest/4	cruise missile attack/6
Filtration/ Washing	local damage/2	formal U.N. protest/4	cruise missile attack/6
Dissolution	major industry damage/5	formal U.N. protest/4	small-scale air strike/8
Chloride Elution	major industry damage/5	formal U.N. protest/4	small-scale air strike/8
Solvent Extraction	major industry damage/5	formal U.N. protest/4	small-scale air strike/8
Fluoride Elution	major industry damage/5	formal U.N. protest/4	small-scale air strike/8
Denitration	major industry damage/5	formal U.N. protest/4	small-scale air strike/8
Oxide Reduction	major industry damage/5	formal U.N. protest/4	small-scale air strike/8
Hydrofluorination	major industry damage/5	formal U.N. protest/4	small-scale air strike/8
Fluorination	major industry damage/5	formal U.N. protest/4	small-scale air strike/8
Mg Reduction	major industry damage/5	formal U.N. protest/4	small-scale air strike/8
Carbothermic Reduction	major industry damage/5	formal U.N. protest/4	small-scale air strike/8
Metal Enrichment	major industry damage/5	terrorist attack in U.S./7	cruise missile attack/6
Aqueous Enrichment	major industry damage/5	terrorist attack in U.S./7	cruise missile attack/6
Gaseous Enrichment	major industry damage/5	terrorist attack in U.S./7	cruise missile attack/6
UF6 Reduction	major industry damage/5	formal U.N. protest/4	small-scale air strike/8

Name	Duration (Months)	Cost (Million 92	Social Impact
Bomb Reduction	**1**	**10.00**	**minor regional impact/5**
Casting	.50	8.00	local damage/2
Forming	.50	7.00	local damage/2
Machine Finishing	1	8.00	local damage/2
Clean/ Inspection	.50	5.00	local damage/2
U Device Assembly	2	20.00	minor national impact/7
Stockpile	**0**	**0.00**	**not available/10**
Chemical Recovery	.25	3.00	not available/10
Oxide Conversion	.50	7.00	**minor regional impact/5**
Direct Oxidation	.50	3.00	**minor regional impact/5**
U/F3 Alloy Dissolution	1	3.00	**minor regional impact/5**
Solvent Extraction	.50	2.00	**minor regional impact/5**
Denitration	.50	4.00	**minor regional impact/5**
Oxide Reduction	.50	2.00	**minor regional impact/5**
ADU Precipitation	.50	7.00	**minor regional impact/5**
Grind/Press	.50	4.00	**minor regional impact/5**
Oxide Reduction	.50	3.00	**minor regional impact/5**
Scintering	.50	2.00	**minor regional impact/5**
Metal Alloy Fabrication	**3**	**10.00**	**minor regional impact/5**
Reactor Operation	**24**	**30.00**	**minor national impact/7**

Name	Economic Impact	Retaliatory Response	Interdiction Effort
Bomb Reduction	**major industry damage/5**	**formal U.N. protest/4**	**small-scale air strike/8**
Casting	**major industry damage/5**	terrorist attack in U.S./7	**cruise missile attack/6**
Forming	**major industry damage/5**	terrorist attack in U.S./7	**cruise missile attack/6**
Machine Finishing	**major industry damage/5**	terrorist attack in U.S./7	**cruise missile attack/6**
Clean/ Inspection	**major industry damage/5**	terrorist attack in U.S./7	**cruise missile attack/6**
U Device Assembly	minor regional damage/7	wide spread terrorism /8	**cruise missile attack/6**
Stockpile	**not available/10**	**not available/10**	**not available/10**
Chemical Recovery	not available/10	not available/10	not available/10
Oxide Conversion	**major industry damage/5**	**formal U.N. protest/4**	**small-scale air strike/8**
Direct Oxidation	**major industry damage/5**	**formal U.N. protest/4**	**small-scale air strike/8**
U/F3 Alloy Dissolution	**major industry damage/5**	**formal U.N. protest/4**	**small-scale air strike/8**
Solvent Extraction	**major industry damage/5**	formal U.N. sanctions/5	**small-scale air strike/8**
Denitration	**major industry damage/5**	formal U.N. sanctions/5	**small-scale air strike/8**
Oxide Reduction	**major industry damage/5**	formal U.N. sanctions/5	**small-scale air strike/8**
ADU Precipitation	**major industry damage/5**	formal U.N. sanctions/5	**small-scale air strike/8**
Grind/Press	**major industry damage/5**	formal U.N. sanctions/5	**small-scale air strike/8**
Oxide Reduction	**major industry damage/5**	formal U.N. sanctions/5	**small-scale air strike/8**
Scintering	**major industry damage/5**	formal U.N. sanctions/5	**small-scale air strike/8**
Metal Alloy Fabrication	**major industry damage/5**	**formal U.N. sanctions/5**	**small-scale air strike/8**
Reactor Operation	**major regional damage/8**	**wide spread terrorism/8**	**small-scale air strikes/8**

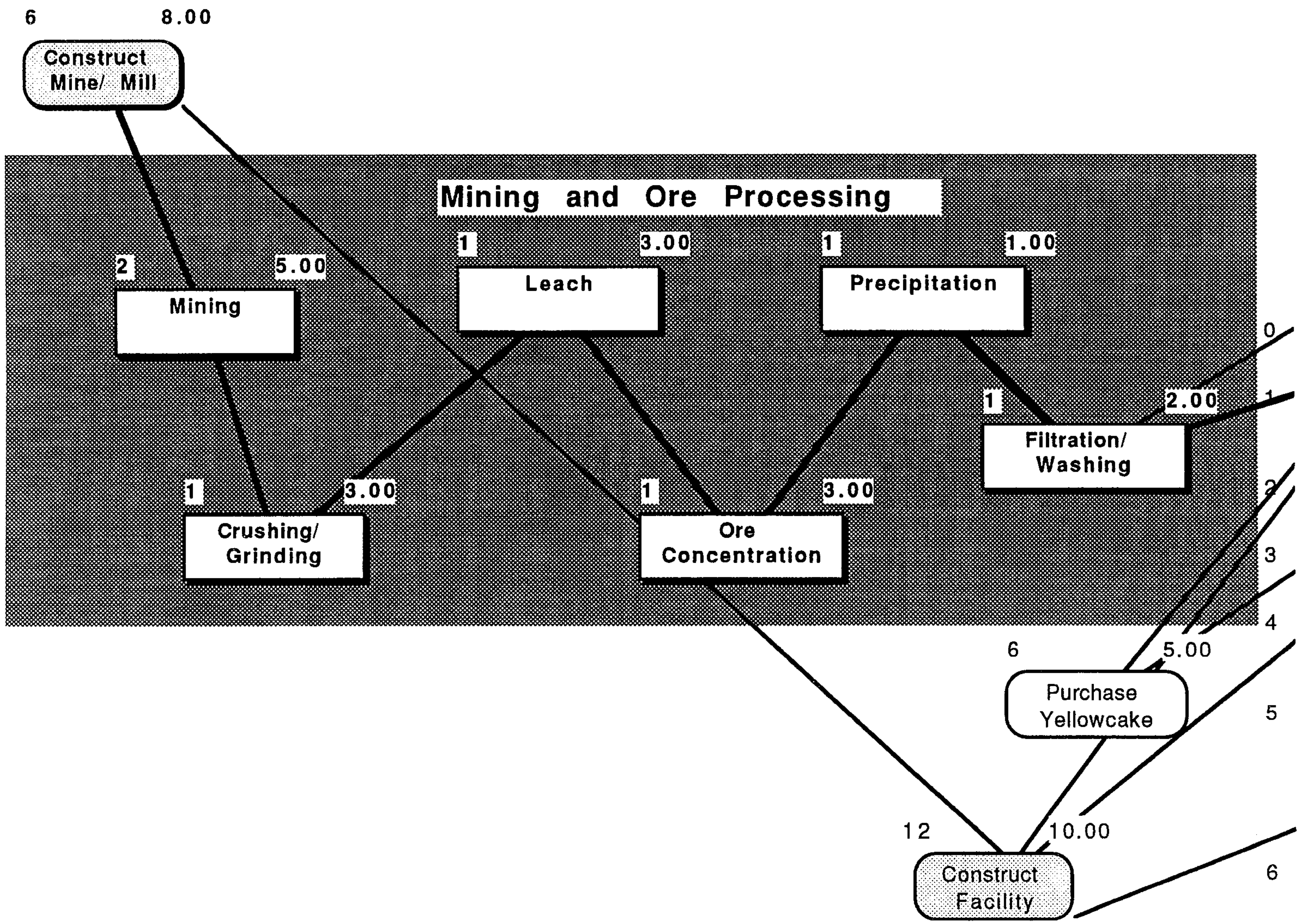
Name	Duration (Months)	Cost (Million 92	Social Impact
Spent Fuel Storage	6	6.00	minimal death/3
Shearing	1	4.00	minimal death/3
Chemical Separation	1	2.00	minimal death/3
Purification	1	5.00	minimal death/3
Oxide Conversion	1	7.00	minimal death/3
Oxide Calcination	.50	4.00	minor regional impact/5
Direct Oxide Reduction	.50	2.00	minor regional impact/5
Molten Salt Extraction	1	2.00	minor regional impact/5
Anode Casting	.50	8.00	minor regional impact/5
Electrorefining	.50	10.00	minor regional impact/5
Casting/ Annealing	.50	6.00	minor regional impact/5
Ingot/ Cast	.50	8.00	minor regional impact/5
Near Shape Casting	.50	7.00	minor regional impact/5
Heat Treat	1	6.00	minor regional impact/5
Rolling/ Blanking	.50	8.00	minor regional impact/5
Press/ Debrimming	.50	7.00	minor regional impact/5
Machining	1	13.00	minor regional impact/5
Assembly/ Joining	1	10.00	minor regional impact/5
Clean/ Inspection	.50	8.00	minor regional impact/5
Pu Device Assembly	1	24.00	minor national impact/7

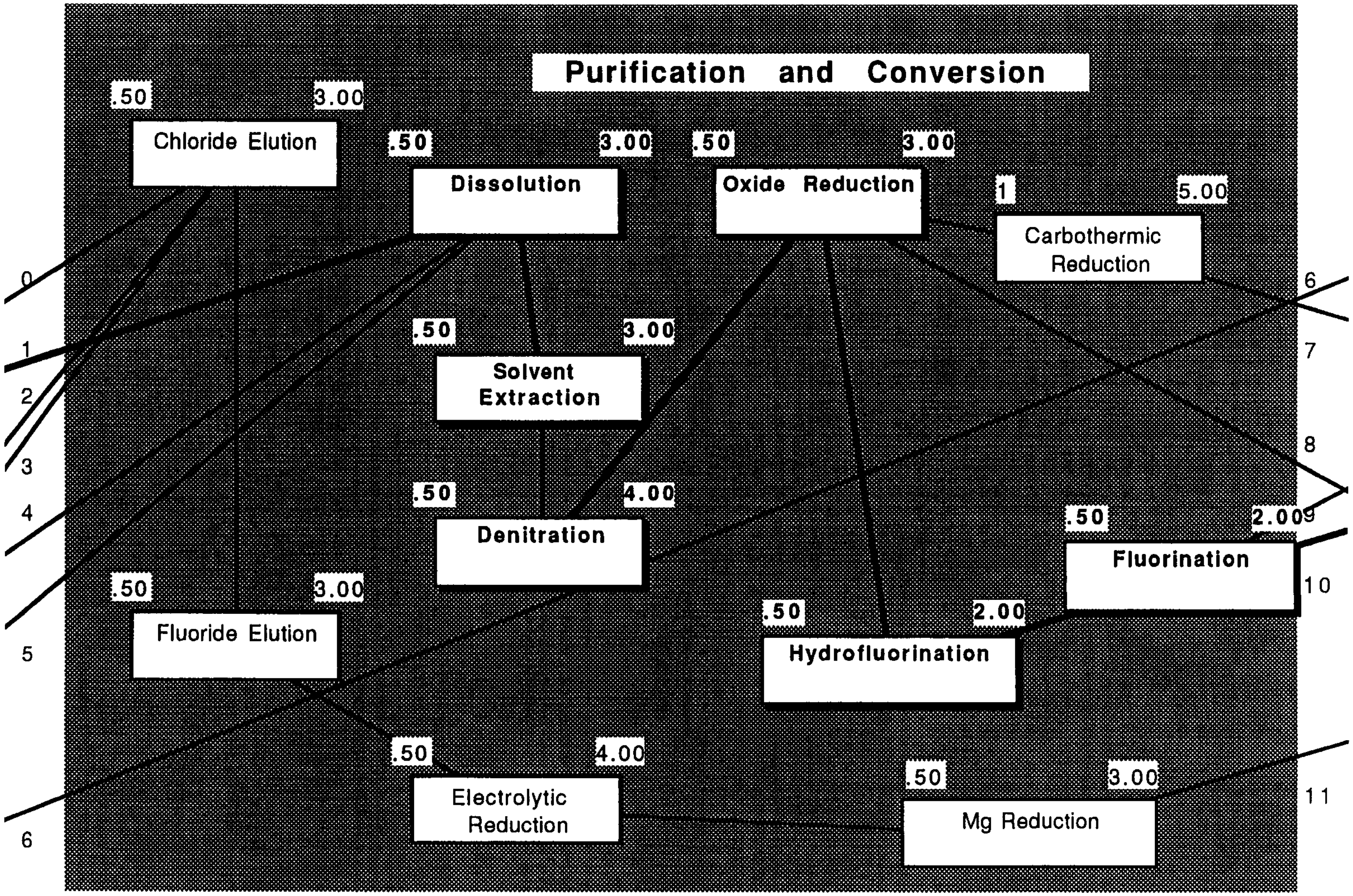
Name	Economic Impact	Retaliatory Response	Interdiction Effort
Spent Fuel Storage	major industry damage/5	terrorist attack in U.S./7	cruise missile attack/6
Shearing	major industry damage/5	terrorist attack on ally/6	cruise missile attack/6
Chemical Separation	major industry damage/5	terrorist attack on ally/6	cruise missile attack/6
Purification	major industry damage/5	terrorist attack on ally/6	cruise missile attack/6
Oxide Conversion	major industry damage/5	terrorist attack on ally/6	cruise missile attack/6
Oxide Calcination	minor regional damage/7	terrorist attack in U.S./7	small-scale air strikes/8
Direct Oxide Reduction	minor regional damage/7	terrorist attack in U.S./7	small-scale air strikes/8
Molten Salt Extraction	minor regional damage/7	terrorist attack in U.S./7	small-scale air strikes/8
Anode Casting	minor regional damage/7	terrorist attack in U.S./7	small-scale air strikes/8
Electrorefining	minor regional damage/7	terrorist attack in U.S./7	small-scale air strikes/8
Casting/ Annealing	major local damage/3	terrorist attack in U.S./7	cruise missile attack/6
Ingot/ Cast	major local damage/3	terrorist attack in U.S./7	cruise missile attack/6
Near Shape Casting	major local damage/3	terrorist attack in U.S./7	cruise missile attack/6
Heat Treat	major local damage/3	terrorist attack in U.S./7	cruise missile attack/6
Rolling/ Blanking	major local damage/3	terrorist attack in U.S./7	cruise missile attack/6
Press/ Debrimming	major local damage/3	terrorist attack in U.S./7	cruise missile attack/6
Machining	major local damage/3	terrorist attack in U.S./7	cruise missile attack/6
Assembly/ Joining	major local damage/3	terrorist attack in U.S./7	cruise missile attack/6
Clean/ Inspection	major local damage/3	terrorist attack in U.S./7	cruise missile attack/6
Pu Device Assembly	minor regional damage/7	wide spread terrorism/8	small-scale air strikes/8

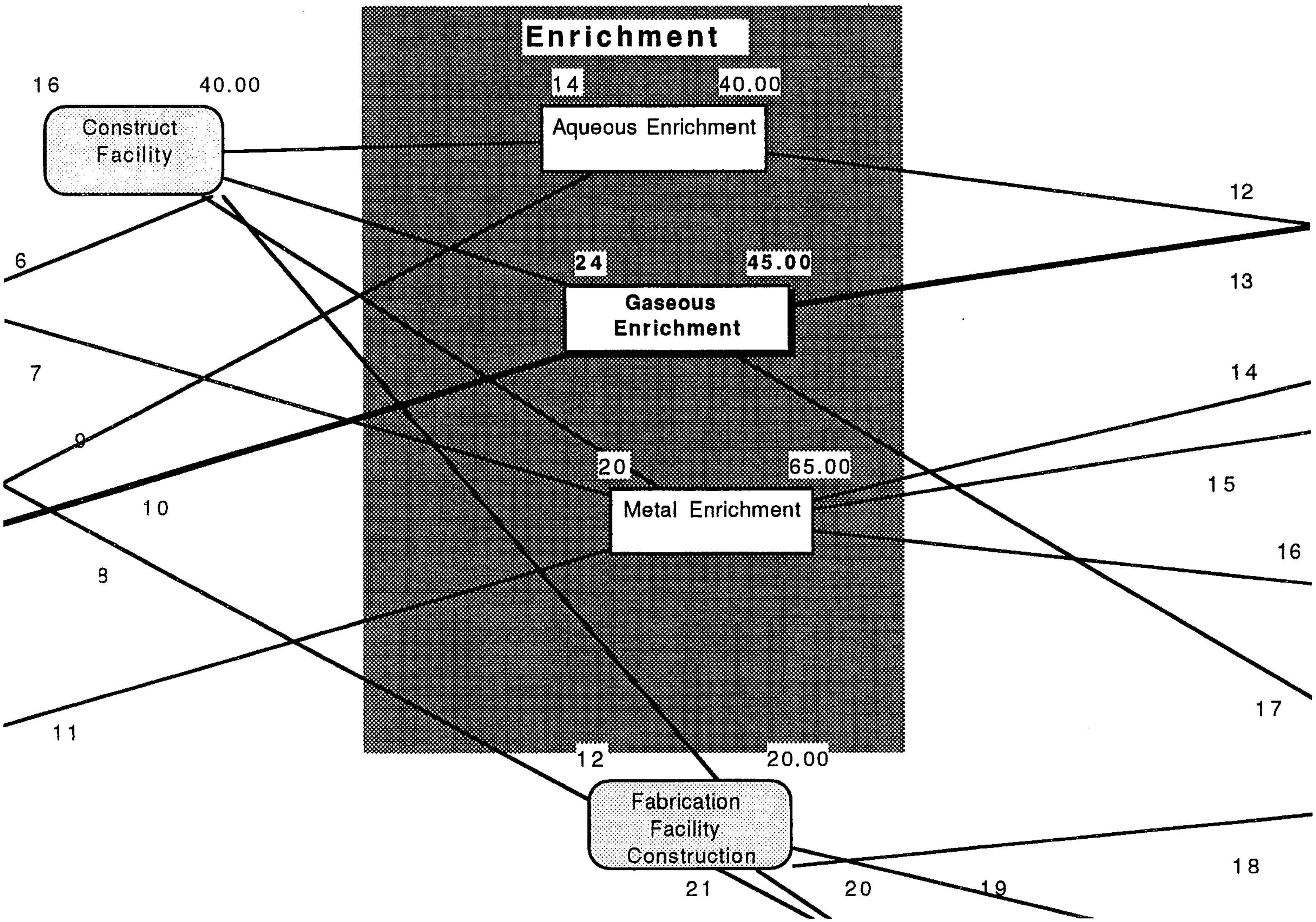
Name	Duration (Months)	Cost (Million 92	Social Impact
Electrolytic Reduction	.50	4.00	**minor regional impact/5**
Purchase Fuel	6	20.00	none/1
Purchase Yellowcake	6	5.00	none/1
Residue Recovery	2	4.00	not available/10
Construct Mine/ Mill	**6**	**8.00**	**minimal death/3**
Construct Facility	12	10.00	**minimal death/3**
Construct Facility	16	40.00	major local damage/4
Reactor Construction	72	120.00	**minor regional impact/5**
Fabrication Facility	12	20.00	**minor regional impact/5**
Construct Reprocessing	24	10.00	**minor regional impact/5**
Leaching/ Dissolving	**0.03**	**0.00**	**not available/10**
Purchase Spent Fuel	12	60.00	none/1

Name	Economic Impact	Retaliatory Response	Interdiction Effort
Electrolytic Reduction	major industry damage/5	formal U.N. protest/4	**cruise missile attack/6**
Purchase Fuel	economic sanctions/6	formal U.N. protest/4	U.N./economic sanctions/4
Purchase Yellowcake	economic sanctions/6	formal U.N. protest/4	U.N./economic sanctions/4
Residue Recovery	not available/10	not available/10	not available/10
Construct Mine/ Mill	**local damage/2**	**formal U.N. protest/4**	**large-scale air strikes/9**
Construct Facility	**local damage/2**	**formal U.N. protest/4**	**cruise missile attack/6**
Construct Facility	local damage/2	**cruise missile attack/6**	**cruise missile attack/6**
Reactor Construction	minor regional damage/7	wide spread terrorism/8	**small-scale air strikes/8**
Fabrication Facility	major local damage/3	**terrorist attack in U.S./7**	**cruise missile attack/6**
Construct Reprocessing	major local damage/3	**terrorist attack in U.S./7**	**small-scale air strikes/8**
Leaching/ Dissolving	**not available/10**	**not available/10**	**not available/10**
Purchase Spent Fuel	economic sanctions/6	formal U.N. protest/4	U.N./economic sanctions/4

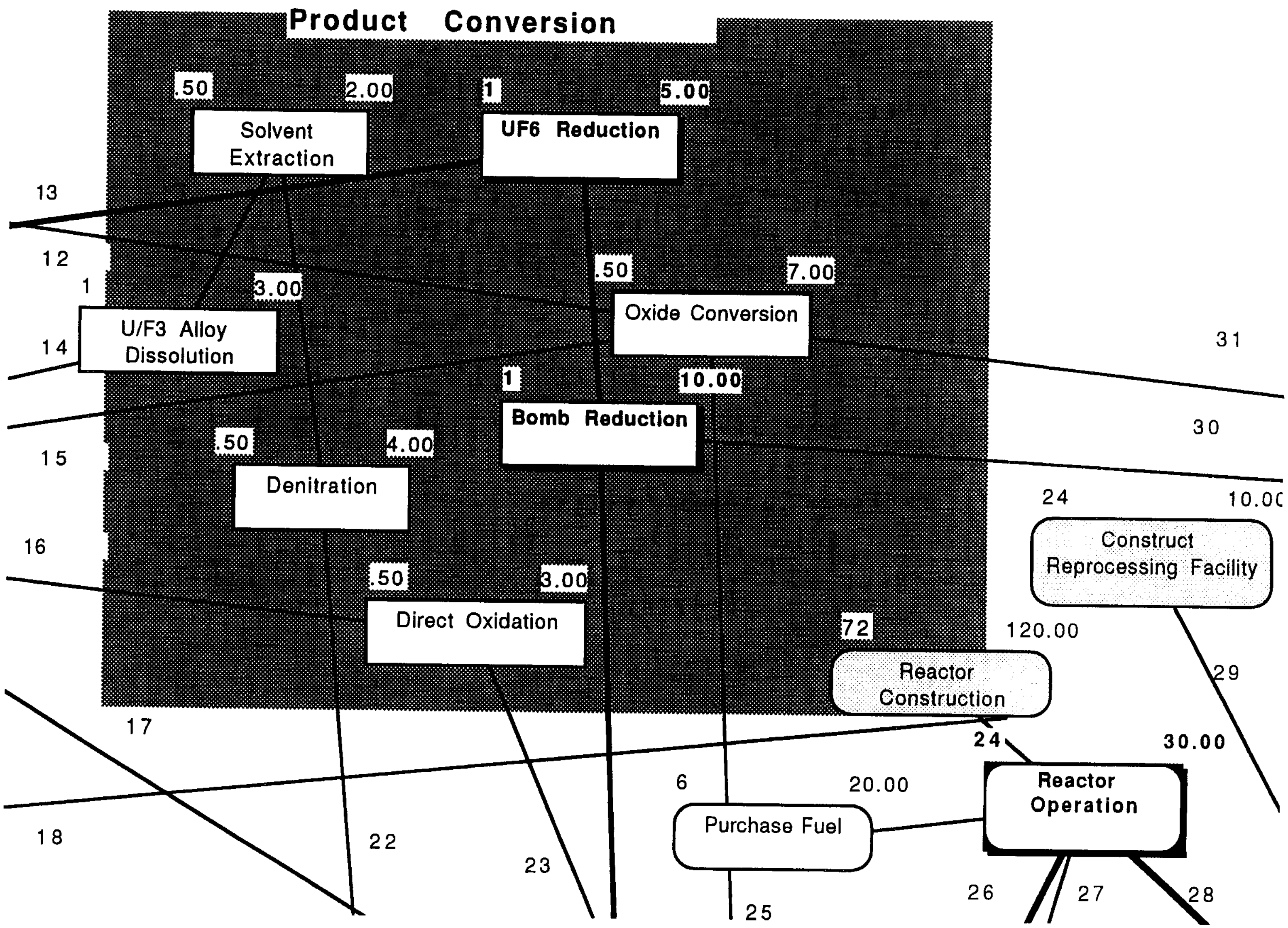
APPENDIX B. PERT/CPM GRAPHICAL DISPLAY



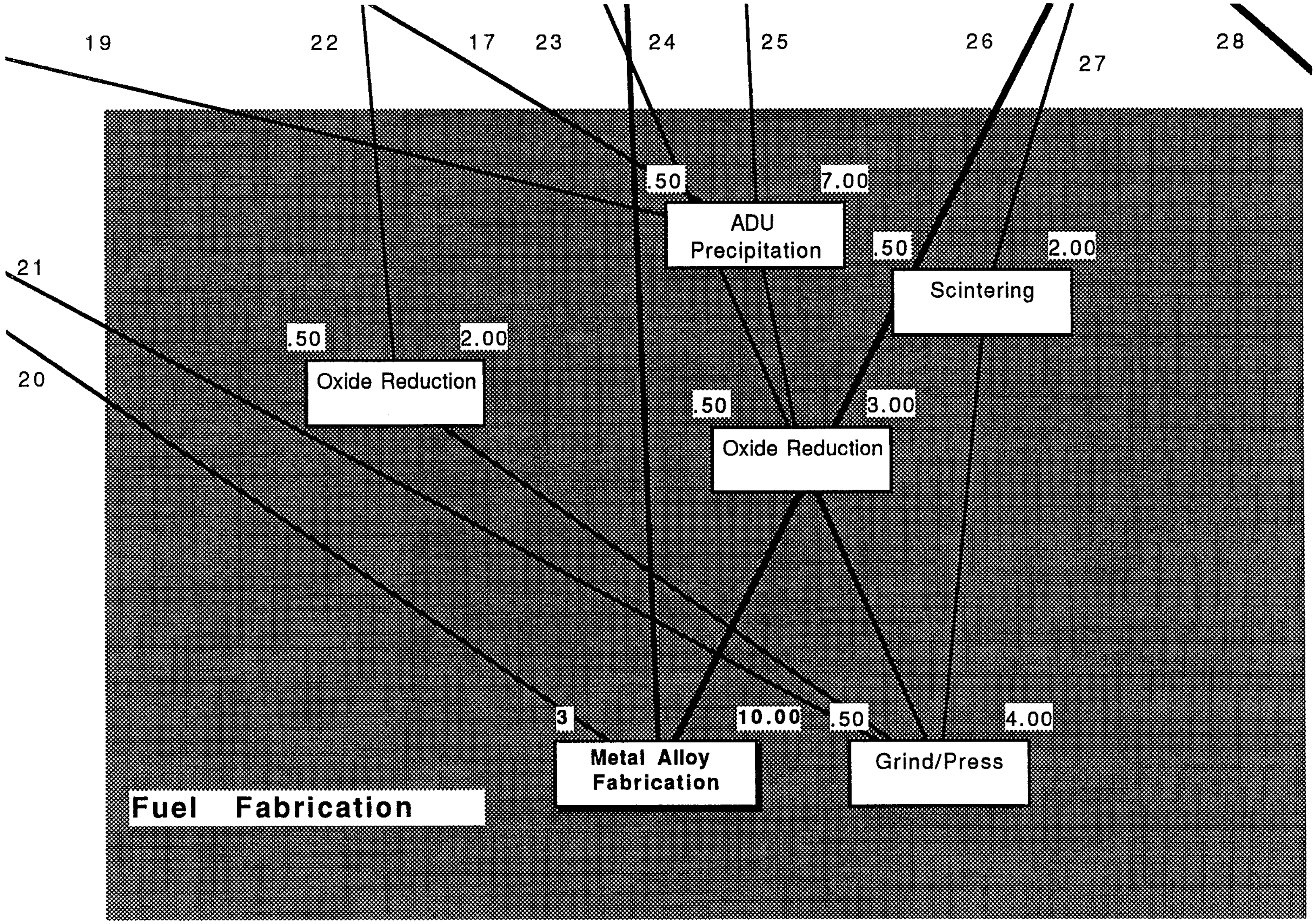

Purification and Conversion
.50
3.00
Chloride Elution
.50
3.00
Dissolution
.50
3.00
Oxide Reduction
1
5.00
Carbothermic Reduction
.50
3.00
Solvent Extraction
.50
4.00
Denitration
.50
3.00
Fluoride Elution
.50
2.00
Fluorination
.50
2.00
Hydrofluorination
.50
4.00
Electrolytic Reduction
.50
3.00
Mg Reduction
0
1
2
3
4
5
6
6
7
8
9
10
11

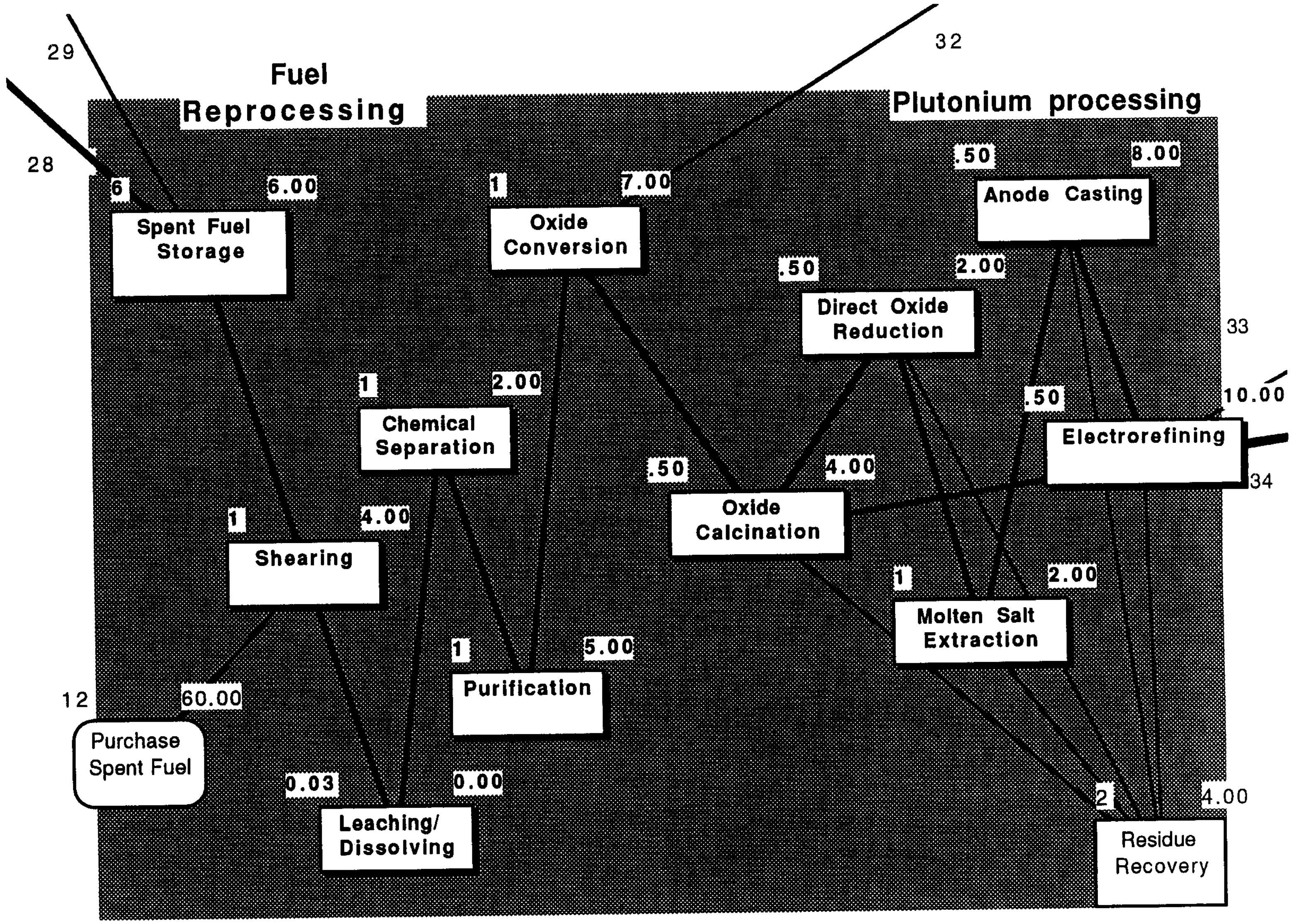


Enrichment
16
40.00
Construct Facility
14
40.00
Aqueous Enrichment
24
45.00
Gaseous Enrichment
20
65.00
Metal Enrichment
12
20.00
Fabrication Facility Construction
6
7
9
10
8
11
12
13
14
15
16
17
18
19
20
21

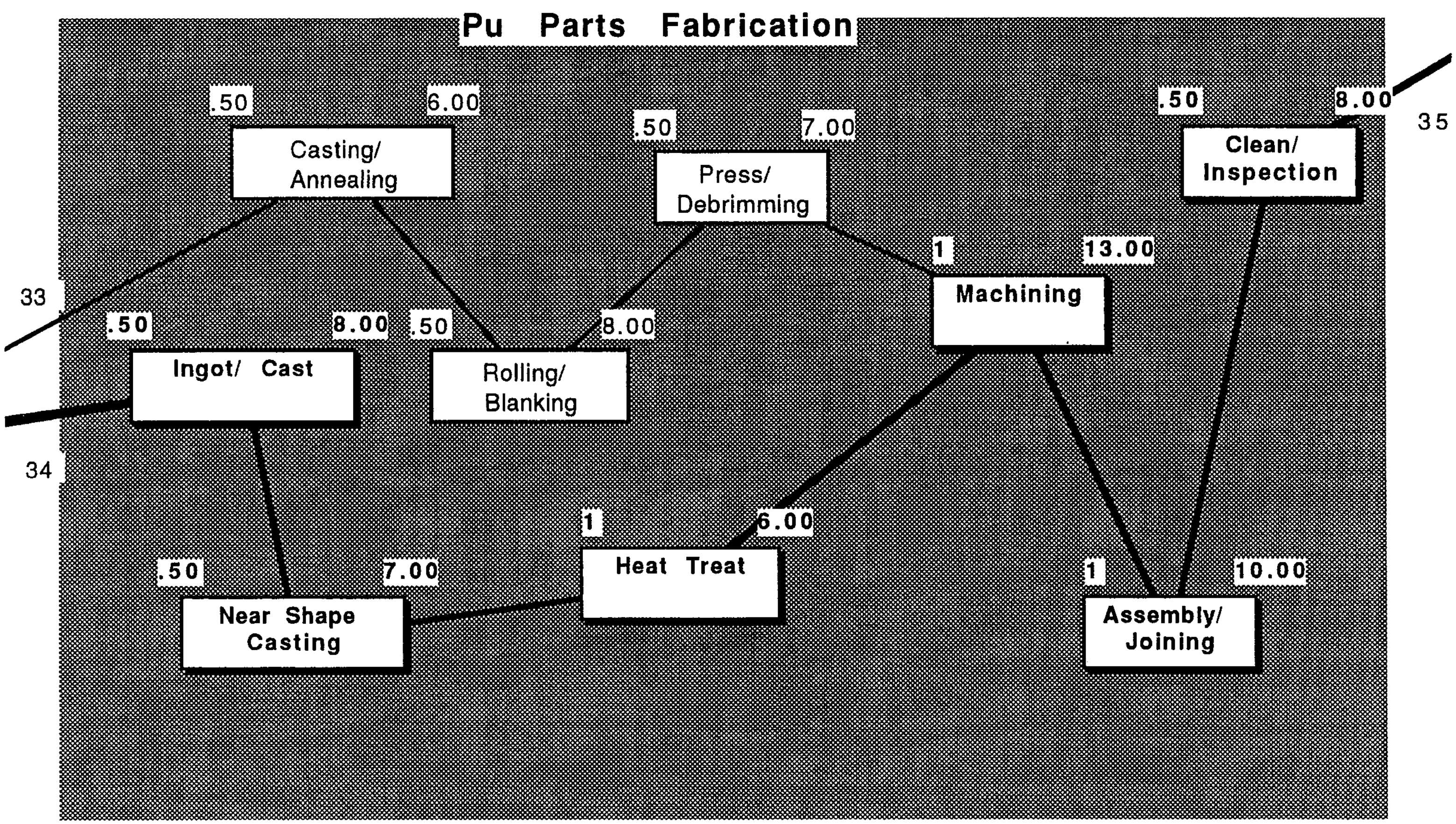


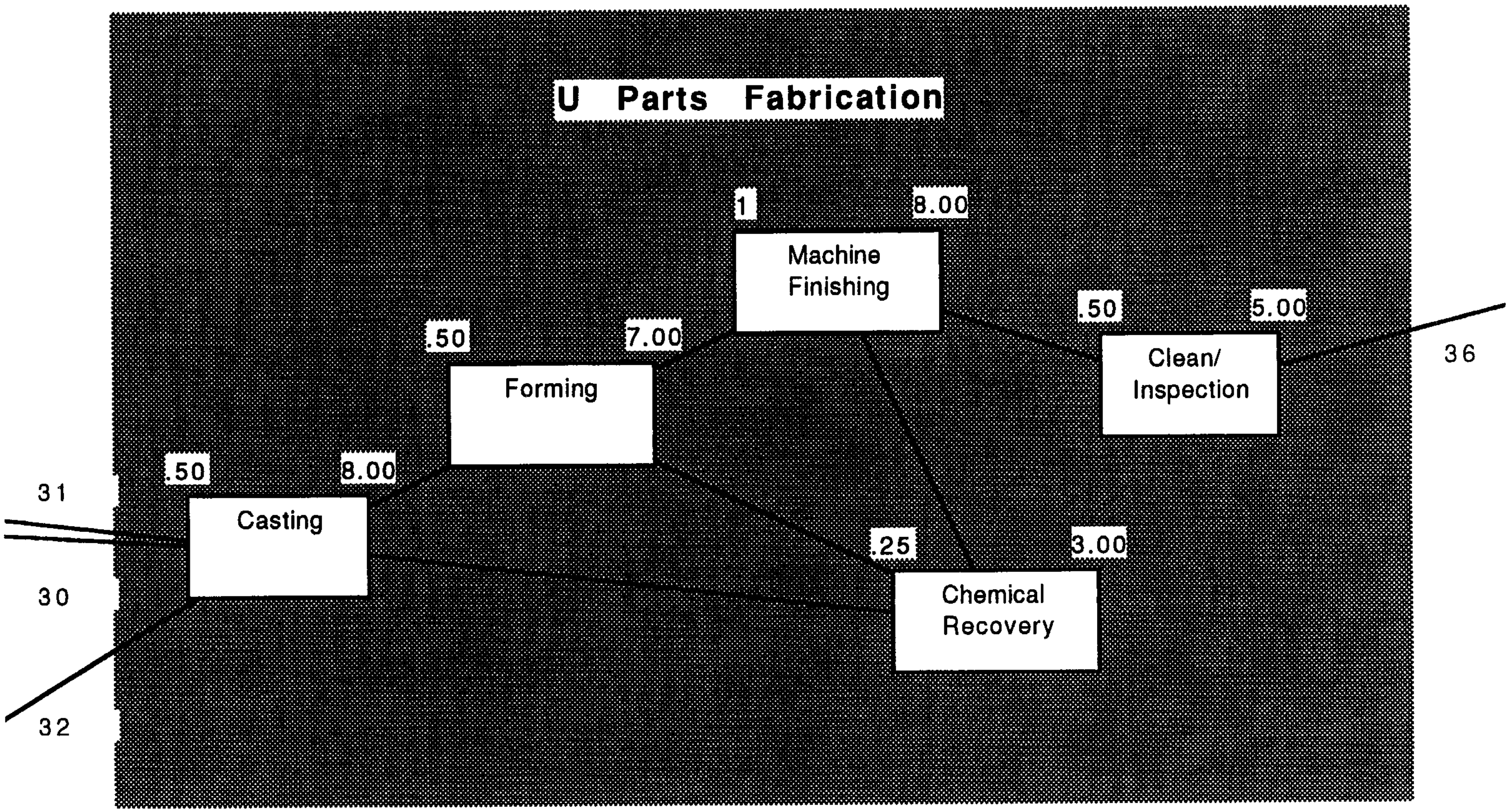
Product Conversion
.50
2.00
Solvent Extraction
1
5.00
UF6 Reduction
13
12
1
3.00
U/F3 Alloy Dissolution
14
.50
7.00
Oxide Conversion
31
1
10.00
Bomb Reduction
15
.50
4.00
Denitration
30
24
10.00
Construct Reprocessing Facility
16
.50
3.00
Direct Oxidation
72
120.00
Reactor Construction
29
17
24
30.00
6
20.00
Reactor Operation
Purchase Fuel
18
22
23
25
26
27
28

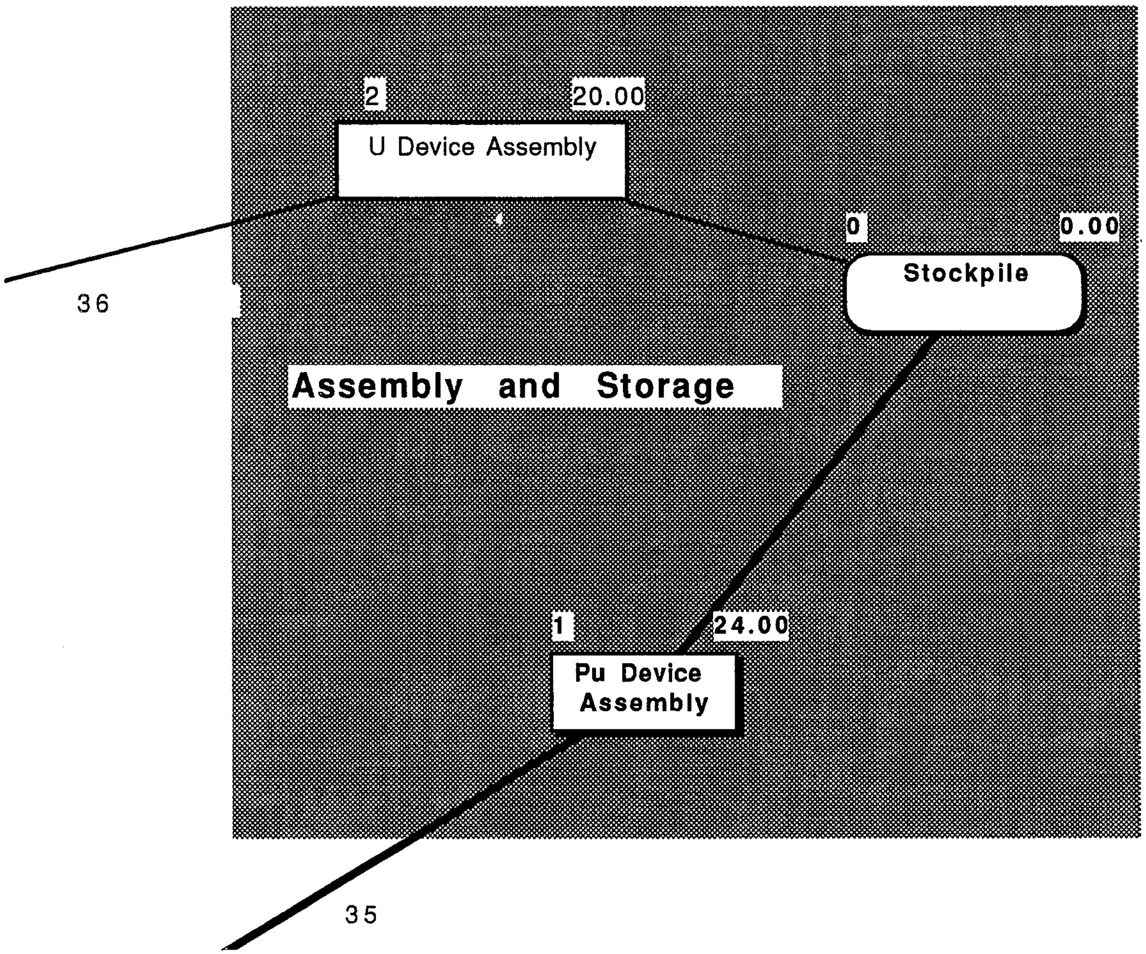

19
22
17
23
24
25
26
27
28
21
20
.50
7.00
ADU Precipitation
.50
2.00
Scintering
.50
2.00
Oxide Reduction
.50
3.00
Oxide Reduction
3
10.00
Metal Alloy Fabrication
.50
4.00
Grind/Press
Fuel Fabrication



Fuel Reprocessing
Plutonium processing
29
28
32
33
34
12
6
6.00
Spent Fuel Storage
1
7.00
Oxide Conversion
.50
8.00
Anode Casting
.50
2.00
Direct Oxide Reduction
1
2.00
Chemical Separation
10.00
.50
Electrorefining
.50
4.00
Oxide Calcination
1
4.00
Shearing
1
2.00
Molten Salt Extraction
1
5.00
Purification
60.00
Purchase Spent Fuel
0.03
0.00
Leaching/ Dissolving
2
4.00
Residue Recovery


Pu Parts Fabrication
.50
6.00
Casting/ Annealing
.50
7.00
Press/ Debrimming
.50
8.00
Clean/ Inspection
35
1
13.00
Machining
33
.50
8.00
Ingot/ Cast
.50
8.00
Rolling/ Blanking
34
1
6.00
Heat Treat
.50
7.00
Near Shape Casting
1
10.00
Assembly/ Joining


U Parts Fabrication
1
8.00
Machine Finishing
.50
5.00
.50
7.00
Clean/ Inspection
36
Forming
.50
8.00
31
Casting
.25
3.00
30
Chemical Recovery
32


2
20.00
U Device Assembly
0
0.00
Stockpile
Assembly and Storage
1
24.00
Pu Device
Assembly
36
35

APPENDIX C. GAMS MODEL FORMULATION

```
$TITLE    Proliferation Interdiction Response Analysis
$STITLE   Brian K. Reed
*------------GAMS AND DOLLAR CONTROL OPTIONS----------------
$OFFUPPER OFFSYMLIST OFFSYMXREF
OPTIONS  LIMCOL =0, LIMROW = 0, SOLPRINT = OFF, DECIMALS = 2
RESLIM = 1000, ITERLIM = 10000, OPTCR = 0.0, SEED = 3141;
*-----------------------------------------------------------
*------------DEFINITIONS AND DATA --------------------------
SET
    I      activities in the process /S,T,Q,1*57/
    ATTR  attributes of activity /CP chosen production path
                                  TIME  activity completion
                                  DTIME induced time delay
                                  COST  cost to build
                                  SOC   social impact
                                  ECON  economic impact
                                  RETAL retaliatory response
                                  EFF  interdiction effort/;

ALIAS       (I,J,K);

TABLE       D(I,J,ATTR)   network data

$INCLUDE PLUTOMET.DAT


SCALAR   MXCOST  minimum acceptable cost/7/
         MXSOC   maximum acceptable social impact/7/
         MXECON  maximum acceptable economic impact/7/
```

```
        MXRETAL maximum acceptable retaliation/7/
        MXEFF   maximum effort expended by interdictor/8/
        INTPTS  number of interdiction points/1/
        ADJ     adjustment for multiple interdiction
                points/.9/;

PARAMETER   INOUT(I)
            /S = 1,
             T = -1/;
*--------------------- MODEL ---------------------------

BINARY VARIABLE
     ACT(I,J)       activities available to interdict
     PATH(I,J)      activities on the induced critical path;

INTEGER VARIABLE
     INTDICT(I,J)   actual activity interdicted;

VARIABLE
     TOTIME         total time to completion;


EQUATIONS
     OBJ            defines the objective function
     FLOWBAL(I)     balance the flow through the path
     STCOST(I,J)    achieve maximum cost
     STSOC(I,J)     achieve minimum social impact
     STECON(I,J)    achieve minimum economic impact
     STRETAL(I,J)   achieve minimum retaliation
     STEFF(I,J)     achieve minimum effort expenditure
     STCCOST        cumulative cost restriction
     STCSOC         cumulative social restriction
```

```
     STCECON        cumulative economic restriction
     STCRETAL       cumulative retaliatory resrtriction
     STCEFF         cumulative interdiction effort
     POINTS         number of interdiction points
     PATHRES(I,J)   restrict value of intdict
     ACTRES(I,J)    restrict value of intdict;

*                   >>> MAXIMIZE <<<
OBJ..
     TOTIME =E=  SUM((I,J)$(D(I,J,"CP") GT 0) ,
     D(I,J,"TIME")*PATH(I,J) + D(I,J,"DTIME")*INTDICT(I,J));

*                   >>> SUBJECT TO <<<

FLOWBAL(I)..
     SUM(J$(D(I,J,"CP") GT 0), PATH(I,J)) -
          SUM(K$(D(K,I,"CP") GT 0), PATH(K,I)) =E= INOUT(I);

STCOST(I,J)$(D(I,J,"CP") GT 0)..
      D(I,J ,"COST")*ACT(I,J) =L= MXCOST;

STSOC(I,J)$(D(I,J,"CP") GT 0)..
      D(I,J ,"SOC")*ACT(I,J) =L= MXSOC;

STECON(I,J)$(D(I,J,"CP") GT 0)..
      D(I,J ,"ECON")*ACT(I,J) =L= MXECON;

STRETAL(I,J)$(D(I,J,"CP") GT 0)..
      D(I,J ,"RETAL")*ACT(I,J) =L= MXRETAL;

STEFF(I,J)$(D(I,J,"CP") GT 0)..
      D(I,J ,"EFF")*ACT(I,J) =L= MXEFF;
```

```
STCCOST$(INTPTS GT 1)..
      SUM((I,J)$(D(I,J,"CP") GT 0),
           D(I,J,"COST")*ACT(I,J)) =L= INTPTS*MXCOST;

STCSOC$(INTPTS GT 1)..
      SUM((I,J)$(D(I,J,"CP") GT 0),
           D(I,J,"SOC")*ACT(I,J)) =L= ADJ*INTPTS*MXSOC;

STCECON$(INTPTS GT 1)..
      SUM((I,J)$(D(I,J,"CP") GT 0),
           D(I,J,"ECON")*ACT(I,J)) =L= ADJ*INTPTS*MXECON;

STCRETAL$(INTPTS GT 1)..
      SUM((I,J)$(D(I,J,"CP") GT 0),
           D(I,J,"RETAL")*ACT(I,J)) =L= ADJ*INTPTS*MXRETAL;
STCEFF$(INTPTS GT 1)..
      SUM((I,J)$(D(I,J,"CP") GT 0),
           D(I,J,"EFF")*ACT(I,J)) =L= INTPTS*MXEFF;

POINTS..
    SUM((I,J)$(D(I,J,"CP") GT 0), INTDICT(I,J) ) =L= INTPTS;

PATHRES(I,J)..
     INTDICT(I,J) =L= ACT(I,J);

ACTRES(I,J)..
      INTDICT(I,J) =L= PATH(I,J);

*-----------------------------------------------------------
```

```
MODEL PIRA /ALL/;
SOLVE  PIRA  USING  MIP  MAXIMIZING  TOTIME;  DISPLAY  ACT.L,
PATH.L, INTDICT.L, TOTIME.L;
```

APPENDIX D. PLUTONIUM-BASED DATA SET

I	J	NAME	CP	TIME	COST	SOC	ECON	RETAL	EFF
S	1	CONST/MINE	1	6	6	3	2	4	9
S	2	CONST/MILL	1	6	6	3	2	4	6
1	2	MINING	1	2	7	2	2	4	9
2	3	CRUSH/GRIND	1	1	8	3	2	4	6
3	4	LEACH	1	1	8	3	2	4	6
4	5	ORE/CONCEN	1	1	8	3	2	4	6
5	6	PRECIP	1	1	9	3	2	4	6
6	7	FILT/WASH	1	1	8	3	2	4	6
Q	7	PURCH/YCAKE	0	6	7	1	6	4	4
S	7	CONST/PURI	1	12	5	3	2	4	6
S	Q	NON-NODE	0	0	0	10	10	10	10
7	8	DISSOLUT	0	.5	8	5	5	4	8
7	9	CHLOR/ELUT	1	.5	8	5	5	4	8
8	10	SOLV/EXTRAC	0	.5	8	5	5	4	8
9	13	FLUOR/ELUT	1	.5	8	5	5	4	8
10	11	DENITRAT	0	.5	7	5	5	4	8
11	12	OXIDE/RED	0	.5	8	5	5	4	8
12	16	HYDROFLUOR	0	.5	8	5	5	4	8
12	15	CARBOTHERM	0	1	7	5	5	4	8
16	17	FLUORINAT	0	.5	8	5	5	4	8
13	14	ELECTROLYT	1	.5	7	5	5	4	8
14	15	Mg/REDUCT	1	.5	8	5	5	4	8
17	18	GASEOUS/ENR	0	24	3	5	5	7	7
S	17	CONST/ENR	0	16	3	4	3	7	6
17	19	AQUEOUS/ENR	0	14	3	5	5	7	7
15	20	METAL/ENR	1	20	2	5	5	7	7
S	15	CONST/ENR	1	16	3	4	3	7	6
6	18	CONST/CONV	0	12	5	3	2	4	6

I	J	NAME	CP	TIME	COST	SOC	ECON	RETAL	EFF
6	19	CONST/CONV	0	12	5	3	2	4	6
6	20	CONST/CONV	1	12	5	3	2	4	6
18	21	UF6/RED	0	1	7	5	5	4	8
19	23	OXIDE/CONV	0	.5	6	5	5	4	8
20	24	UF3/ALLOY	1	1	8	5	5	4	8
20	36	DIR/OXIDAT	0	.5	8	5	5	4	8
22	23	OXIDE/CONV	0	.5	6	5	5	4	8
21	26	BOMB/REDUCT	0	1	5	5	5	5	8
15	26	CONTR/FABRI	0	12	4	5	3	7	6
17	26	CONTR/FABRI	0	12	4	5	3	7	6
26	27	CASTING	0	.5	6	2	5	7	6
23	27	CASTING	0	.5	6	2	5	7	6
27	28	FORMING	0	.5	6	2	5	7	6
28	29	MACH/FIN	0	1	6	2	5	7	6
29	30	CLEAN/INSP	0	.5	7	2	5	7	6
30	31	U/DEV/ASSEM	0	2	4	7	7	8	6
31	T	STOCKPILE	1	0	10	10	10	10	10
15	23	CONTR/FACIL	0	20	4	5	3	7	6
15	34	CONTR/FACIL	1	20	4	5	3	7	6
17	23	CONTR/FACIL	0	20	4	5	3	7	6
23	32	ADU/PRECIP	0	.5	6	5	5	5	8
18	32	ADU/PRECIP	0	.5	6	5	5	5	8
26	38	MET/ALLY/FAB	0	3	5	5	5	5	8
24	33	SOLV/EXTRAC	1	.5	8	5	5	5	8
33	34	DENITRAT	1	.5	7	5	5	5	8
34	36	OXIDE/RED	1	.5	8	5	5	5	8
32	36	OXIDE/RED	0	.5	8	5	5	5	8
36	37	GRIND/PRESS	1	.5	7	5	5	5	8
37	38	SCINTERING	1	.5	8	5	5	5	8
S	38	REACTOR/CONS	1	72	1	5	7	8	8

I	J	NAME	CP	TIME	COST	SOC	ECON	RETAL	EFF
Q	38	PURCH/FUEL	0	6	4	1	6	4	4
38	39	REACTOR/OPS	1	24	3	7	8	8	8
36	39	CONST/REPROS	1	24	5	5	3	7	8
39	40	SPENT/FUEL	1	6	6	3	7	7	6
S	39	PURCH/SPENT	0	12	2	1	6	4	4
40	41	SHEAR/LEACH	1	1	7	3	5	6	6
41	42	CHEM/SEPAR	1	1	7	3	5	6	6
42	43	PURIFICAT	1	1	7	3	5	6	6
43	44	OXIDE/CONV	1	1	6	3	5	6	6
43	27	OXIDE/CONV	0	1	6	3	5	6	6
38	44	CONST/REPROS	1	18	5	5	3	7	8
44	45	OXIDE/CALCIF	1	.5	7	5	7	7	8
44	49	OXIDE/CALCIF	1	.5	7	5	7	7	8
45	46	DIR/OX/RED	1	.5	8	5	7	7	8
46	47	MOLT/SALT/EX	1	1	8	5	7	7	8
47	48	ANODE/CAST	1	.5	6	5	7	7	8
48	49	ELECTROREFIN	1	.5	5	5	7	7	8
38	49	CONTR/FABRI	1	12	4	5	3	7	6
49	50	CAST/ANNEAL	1	.5	6	5	3	7	6
50	51	ROLL/BLANK	1	.5	6	5	3	7	6
51	54	PRESS/DEBRIM	1	.5	7	5	3	7	6
54	55	MACHINING	1	1	5	5	3	7	6
49	52	INGOT/CAST	1	.5	6	5	3	7	6
52	53	NEARSHAP/CAS	1	.5	6	5	3	7	6
53	54	HEAT/TREAT	1	1	6	5	3	7	6
54	55	ASSEM/JOIN	1	1	5	5	3	7	6
55	56	CLEAN/INSP	1	.5	6	5	3	7	6
56	31	PU/DEV/ASSEM	1	2	4	7	7	8	8

APPENDIX E. MODEL OUTPUT

A. URANIUM-BASED, GASEOUS ENRICHMENT NUCLEAR WEAPONS PROGRAM

1. Zero Interdiction Points

Proliferation Interdiction Response Analysis Execution

VARIABLE ACT.L activities available to interdict

(ALL 0.00)

VARIABLE PATH.L activities on the induced critical path

	T	1	2	3	4	5
S		1.00				
1			1.00			
2				1.00		
3					1.00	
4						1.00
31	1.00					

+	6	7	8	10	11	12
5	1.00					
6		1.00				
7			1.00			
8				1.00		
10					1.00	
11						1.00

+	16	17	18	21	26	27
12	1.00					
16		1.00				
17			1.00			
18				1.00		
21					1.00	
26						1.00

+	28	29	30	31
27	1.00			
28		1.00		
29			1.00	
30				1.00

VARIABLE INTDICT.L actual activity interdicted
(ALL 0.00)

VARIABLE TOTIME.L = 46.50 total time to completion

2. One Interdiction Point

Proliferation Interdiction Response Analysis Execution

VARIABLE ACT.L activities available to interdict

	18
17	1.00

VARIABLE PATH.L activities on the induced critical path

	T	1	2	3	4	5
S		1.00				
1			1.00			
2				1.00		
3					1.00	
4						1.00
31	1.00					

+	6	7	8	10	11	12
5	1.00					
6		1.00				
7			1.00			
8				1.00		
10					1.00	
11						1.00

+	16	17	18	21	26	27
12	1.00					
16		1.00				
17			1.00			
18				1.00		
21					1.00	
26						1.00

+	28	29	30	31
27	1.00			
28		1.00		
29			1.00	
30				1.00

VARIABLE INTDICT.L actual activity interdicted

	18
17	1.00

VARIABLE TOTIME.L = 70.50 total time to completion

3. Two Interdiction Points

Proliferation Interdiction Response Analysis Execution

VARIABLE ACT.L activities available to interdict

	7	18
S	1.00	
17		1.00

VARIABLE PATH.L activities on the induced critical path

	T	7	8	10	11	12
S		1.00				
7			1.00			
8				1.00		
10					1.00	
11						1.00
31	1.00					

+	16	17	18	21	26	27
12	1.00					
16		1.00				
17			1.00			
18				1.00		
21					1.00	
26						1.00

+	28	29	30	31
27	1.00			
28		1.00		
29			1.00	
30				1.00

VARIABLE INTDICT.L actual activity interdicted

	7	18
S	1.00	
17		1.00

VARIABLE TOTIME.L = 81.50 total time to completion

4. Three Interdiction Points

Proliferation Interdiction Response Analysis Execution

VARIABLE ACT.L activities available to interdict

	17	18	21
S	1.00		
17		1.00	
18			1.00

VARIABLE PATH.L activities on the induced critical path

	T	17	18	21	26	27
S		1.00				
17			1.00			
18				1.00		
21					1.00	
26						1.00
31	1.00					

+	28	29	30	31
27	1.00			
28		1.00		
29			1.00	
30				1.00

VARIABLE INTDICT.L actual activity interdicted

	17	18	21
S	1.00		
17		1.00	
18			1.00

VARIABLE TOTIME.L = 87.50 total time to completion

B. PLUTONIUM-BASED, METAL ENRICHMENT NUCLEAR WEAPONS PROGRAM

1. Zero Interdiction Points

Proliferation Interdiction Response Analysis Execution

VARIABLE ACT.L activities available to interdict

(ALL 0.00)

VARIABLE PATH.L activities on the induced critical path

	T	31	38	39	40	41
S			1.00			
31	1.00					
38				1.00		
39					1.00	
40						1.00
57		1.00				

+	42	43	44	45	46	47
41	1.00					
42		1.00				
43			1.00			
44				1.00		
45					1.00	
46						1.00

+	48	49	52	53	54	55
47	1.00					
48		1.00				
49			1.00			
52				1.00		
53					1.00	
54						1.00

+	56	57
55	1.00	
56		1.00

VARIABLE INTDICT.L actual activity interdicted
(ALL 0.00)

VARIABLE TOTIME.L = 115.50 total time to completion

2. One Activity Interdiction

Proliferation Interdiction Response Analysis Execution

VARIABLE ACT.L activities available to interdict

	40
39	1.00

VARIABLE PATH.L activities on the induced critical path

	T	31	38	39	40	41
S			1.00			
31	1.00					
38				1.00		
39					1.00	
40						1.00
57		1.00				

+	42	43	44	45	46	47
41	1.00					
42		1.00				
43			1.00			
44				1.00		
45					1.00	
46						1.00

+	48	49	52	53	54	55
47	1.00					
48		1.00				
49			1.00			
52				1.00		
53					1.00	
54						1.00

+	56	57
55	1.00	
56		1.00

VARIABLE INTDICT.L actual activity interdicted

	40
39	1.00

VARIABLE TOTIME.L = 121.50 total time to completion

3. Two Activity Interdiction

Proliferation Interdiction Response Analysis Execution

VARIABLE ACT.L activities available to interdict

	40	41
39	1.00	
40		1.00

VARIABLE PATH.L activities on the induced critical path

	T	31	38	39	40	41
S			1.00			
31	1.00					
38				1.00		
39					1.00	
40						1.00
57		1.00				

+	42	43	44	45	46	47
41	1.00					
42		1.00				
43			1.00			
44				1.00		
45					1.00	
46						1.00

+	48	49	52	53	54	55
47	1.00					
48		1.00				
49			1.00			
52				1.00		
53					1.00	
54						1.00

+	56	57
55	1.00	
56		1.00

VARIABLE INTDICT.L actual activity interdicted

	40	41
39	1.00	
40		1.00

VARIABLE TOTIME.L = 122.50 total time to completion

4. Three Activity Interdiction

Proliferation Interdiction Response Analysis Execution

VARIABLE ACT.L activities available to interdict

	7	20	39
S	1.00		
15		1.00	
36			1.00

VARIABLE PATH.L activities on the induced critical path

	T	7	9	13	14	15
S		1.00				
7			1.00			
9				1.00		
13					1.00	
14						1.00
31	1.00					

+	20	24	31	33	34	36
15	1.00					
20		1.00				
24				1.00		
33					1.00	
34						1.00
57			1.00			

+	39	40	41	42	43	44
36	1.00					
39		1.00				
40			1.00			
41				1.00		
42					1.00	
43						1.00

+	45	46	47	48	49	52
44	1.00					
45		1.00				
46			1.00			
47				1.00		
48					1.00	
49						1.00

+	53	54	55	56	57
52	1.00				
53		1.00			
54			1.00		
55				1.00	
56					1.00

VARIABLE INTDICT.L actual activity interdicted

	7	20	39
S	1.00		
15		1.00	
36			1.00

VARIABLE TOTIME.L = 136.00 total time to completion

GLOSSARY

Atomic Bomb A bomb whose energy comes from the fission of uranium or plutonium.

Chain Reaction The continuing process of nuclear fissioning in which the neutrons released from a fission trigger at least one other nuclear fission. In a nuclear weapon an extremely rapid, multiplying chain reaction causes the explosive release of energy. In a reactor, the pace of the chain reaction is controlled to produce heat (in a power reactor) or large quantities of neutrons (in a research or production reactor.

Chemical Processing Chemical treatment of materials to separate specific usable materials.

Critical Mass Minimum amount of fissionable material required to sustain a chain reaction.

Depleted Uranium Uranium having a smaller concentration of uranium-235 than the 0.7 percent found in natural uranium. A by-product of the enrichment process.

Enrichment The process of increasing the concentration of one isotope of a given element (in the case of uranium, increasing the concentration of uranium-235).

Fertile Material composed of atoms which readily absorb neutrons to produce fissionable materials. Fertile material alone cannot sustain a chain reaction.

Fission The process by which a neutron strikes the nucleus and splits it into fragments. During the process of nuclear fission, several neutrons are emitted at high speed, and heat and light are released.

Fissile Material Material composed of atoms which readily fission when struck by a neutron. Uranium-235 and plutonium-239 are some examples of fissile materials.

Fusion The formation of a heavier nucleus from lighter ones (such as hydrogen isotopes), with the attendant release of energy (as in a hydrogen bomb).

Gas Centrifuge Process A method of isotope separation in which heavy gaseous atoms or molecules are separated from the light ones by centrifugal force. See ultracentrifuge.

Gaseous Diffusion A method of isotope separation based on the fact that gas atoms or molecules with different masses will diffuse through a porous barrier at different rates. The method used to separate uranium-235 from uranium-238. It requires large gaseous diffusion plants and significant amounts of electricity.

Highly Enriched Uranium Uranium in which the percentage of uranium-235 nuclei has been increased from the natural level of 0.7 percent to some level greater than 20 percent, usually around 90 percent.

Hydrogen Bomb A nuclear weapon that derives its energy largely from fusion. Also known as a thermonuclear bomb.

Irradiation Exposure to a radioactive source; usually in the case of fuel materials, being placed in an operating nuclear reactor.

Isotopes Atoms having the same number of protons, but a different number of neutrons. Two isotopes of the same atom are very similar and difficult to separate by normal chemical means. Isotopes can have very different nuclear properties, however. For example, one isotope may fission readily while another isotope of the same atom may not fission at all. An isotope is specified by its atomic mass number (the number of protons plus neutrons) following the symbol denoting the chemical element (e.g., U^{235} is an isotope of uranium).

Jet-nozzle Enrichment Process a process of uranium enrichment that uses both uranium hexafluoride and a light gas flowing at high speed through a nozzle along curved walls.

Kiloton The energy of a nuclear explosion that is equivalent to an explosion of 1,000 tons of TNT.

Light-water Reactor A reactor that uses ordinary water (H_2O) as a moderator and coolant and low-enriched uranium as fuel.

Low-enriched Uranium Uranium in which the percentage of uranium-235 nuclei has been increased from the natural level of 0.7 percent to less than 20 percent, usually around 3 to 6 percent. With the increased level of fissile material, low-enriched uranium can sustain a chain reaction when immersed in light-water and is used as fuel in light-water reactors.

Medium-enriched Uranium Uranium in which the percentage of uranium-235 nuclei has been increased from the natural level of 0.7 percent to between 20 and 50 percent. (Potentially usable for nuclear weapons, but very large quantities needed.)

Milling A process in the uranium fuel cycle by which ore containing only a small percentage of uranium oxide (U_3O_8) is converted into material containing a high percentage (80 percent) of U_3O_8, often referred to as yellowcake.

Natural Uranium Uranium as found in nature, containing 0.7 percent of uranium-235, 99.3 percent of urnium-238 and a trace of uranium-234.

Neutron An uncharged particle, with a mass slightly greater than that of a proton, found in the nucleus of every atom heavier than hydrogen.

Nuclear Energy The energy liberated by a nuclear reaction (fission or fusion) or by spontaneous radioactivity.

Nuclear Fuel Basis chain-reacting material, including both fissile and fertile materials. Commonly used nuclear fuels are natural uranium and low-enriched uranium; high-enriched uranium and plutonium are used in some reactors.

Nuclear Fuel Cycle The set of chemical and physical operations needed to prepare nuclear materials for use in reactors and to dispose of or recycle the material after its removal from the reactor. Existing cycles begin with uranium as a natural resource and create plutonium as a by-product.

Nuclear Fuel Fabrication Plant A facility where the nuclear material (e.g., enriched or natural uranium) is fabricated in fuel elements to be inserted into a reactor.

Nuclear Reactor A mechanism fuel by fissionable materials that give off neutrons, thereby inducing heat. Reactors are of three general types: power, production and research.

Nuclear Waste The radioactive by-products formed by fission and other nuclear processes in a reactor.

Nuclear Weapons A collective term for atomic and hydrogen bombs. Weapons based on a nuclear explosion.

Plutonium-239 A fissile isotope occurring naturally in only minute quantities, which is manufactured artificially when uranium-238, through irradiation, captures and extra neutron. It is one of two materials that have been used for the core of nuclear weapons, the other being highly enriched uranium.

Plutonium-240 A fissile isotope produced in reactors when a plutonium-239 atom absorbs a neutron instead of fissioning. Its presence complicates the construction of nuclear explosives because of a high rate of spontaneous fission.

Power Reactor A reactor designed to produce electricity.

Production Reactor A reactor designed primarily for large-scale production of plutonium-239 by neutron irradiation of uranium-238.

Reprocessing Chemical treatment of spent reactor fuel to separate the plutonium and uranium from the unwanted radioactive waste by-products and (under present plans) from each other.

Research Reactor A reactor primarily designed to supply neutrons for experimental purposes.

Spent Fuel Fuel element that have been removed from the reactor because they contain too little fissile and fertile material and too high a concentration of unwanted radioactive by-products to sustain reactor operations. Spent for is both thermally and radioactively hot.

Thorium-232 A fertile material.

Tritium the heaviest hydrogen isotope, containing one proton and two neutrons in the nucleus. In a fission weapon, tritium produces excess neutrons, which set off additional reactions in the weapons fissile material. In this way tritium can either reduce the required fissile material, or multiply (i.e., boost) the weapon's destructive power as much as five times. In fusion reactions, tritium and deuterium, another hydrogen isotope, bond tat very high temperatures, releasing approximately 14 million electron-volts of energy per set of neutrons.

Ultracentrifuge A rotating vessel that can be used for the enrichment of uranium. The heavier isotopes of uranium hexafluoride gas concentrate at the walls of the rotating centrifuge and are drawn off.

Uranium A radioactive element with the atomic number 92 and, as found in ores, an average atomic weight of 238. The two principal natural isotopes are uranium-235 (0.7 percent of natural uranium), which is fissionable, and uranium-238 (99.3 percent of natural uranium), which is fertile.

Uranium-233 (U^{233}) A fissionable isotope bred in thorium-232. Theoretically an excellent material for nuclear weapons, but is not known to have been used for that purpose. Can be used as reactor fuel.

Uranium-235 (U^{235}) The only naturally occurring fissionable isotope. Natural uranium contains 0.7 percent; light-water reactors use about 3 percent and weapons grade, highly enriched uranium normally consists of 93 percent of this isotope.

Uranium-238 (U^{238}) A fertile material. Natural uranium is composed of approximately 99.3 percent of this isotope.

Uranium Dioxide (UO_2) Purified uranium. The form of natural uranium used in heavy water reactors. Produced as a powder, uranium dioxide is, in turn, fabricated into fuel elements.

Uranium Oxide (U_3O_8) The most common oxide of uranium found in ores. U_3O_8 is extracted form the ore during the milling process. The ore typically contains only 0.1 percent; yellowcake, the product of the milling process, contains about 80 percent U_3O_8.

Uranium Hexafluoride (UF_6) A volatile compound of uranium and fluorine. UF_6 is a solid at atmospheric pressure and room temperature, but can be transformed into a gas by heating. UF_6 gas is the feed stock in all uranium enrichment processes and is sometimes produced as an intermediate product in the purification of yellowcake to produce uranium oxide.

Weapons Grade Nuclear material of the type most suitable for nuclear weapons, i.e., uranium enriched to 93 percent U^{235} or plutonium that is primarily P^{239}.

Weapons-Usable Fissionable material that is weapons-grade or, though less than ideal for weapons, can still be used to make a nuclear explosive.

Yellowcake A concentrate produced during the milling process that contains about 80 percent uranium oxide. In preparation for uranium enrichment, the yellowcake is converted to uranium hexafluoride gas. In the preparation of natural uranium reactor fuel, yellowcake is processed into purified uranium dioxide.

Yield The total energy released in a nuclear explosion. It is usually expressed in equivalent tons of TNT.

LIST OF REFERENCES

1. Spector, L.S., *Going Nuclear*, Ballinger Publishing Co., 1987.

2. Nacht, M., *The Age of Vulnerability: Threats to the Nuclear Stalemate,* The Brookings Institute, 1985.

3. Lewis, J.W. and Litai, X., *China Builds the Bomb,* Stanford University Press, 1988.

4. U.S. Congress, Office of Technology Assessment, *Proliferation of Weapons of Mass Destruction: Assessing the Risks,* OTA-ISC-559, U.S. Government Printing Office, August 1993.

5. Spector, L.S., *Nuclear Ambitions: The Spread of Nuclear Weapons 1989-1990,* Westview Press, 1990.

6. U.S. Congress, Office of Technology Assessment, *Technologies Underlying Weapons of Mass Destruction,* OTA-BP-ISC-115, U.S. Government Printing Office, December 1993.

7. Hillier, F.S. and Lieberman, G.J., *Introduction to Operations Research,* McGraw-Hill Publishing Company, 1990.

8. MacProject Pro, Claris Corpoartion, Santa Clara, CA 95052-8168, 1992.

9. Brooke, A., Kendrick, D. and Meeraus, A., *GAMS: A Users Guide, Release 2.25,* Scientific Press, 1992.

10. XA Version 7, Sunset Software Technology, San Marino,CA 91108, 1992.

11. Wood, R.K., "Deterministic Network Interdiction," *Mathematical Computer Modelling,* vol. 17, no. 2,pp. 1-18, Monterey, CA, 1993.

12. Steinruauf, R., A Network Interdiction Model, M.S. Thesis, Naval Postgraduate School, May 1991.

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